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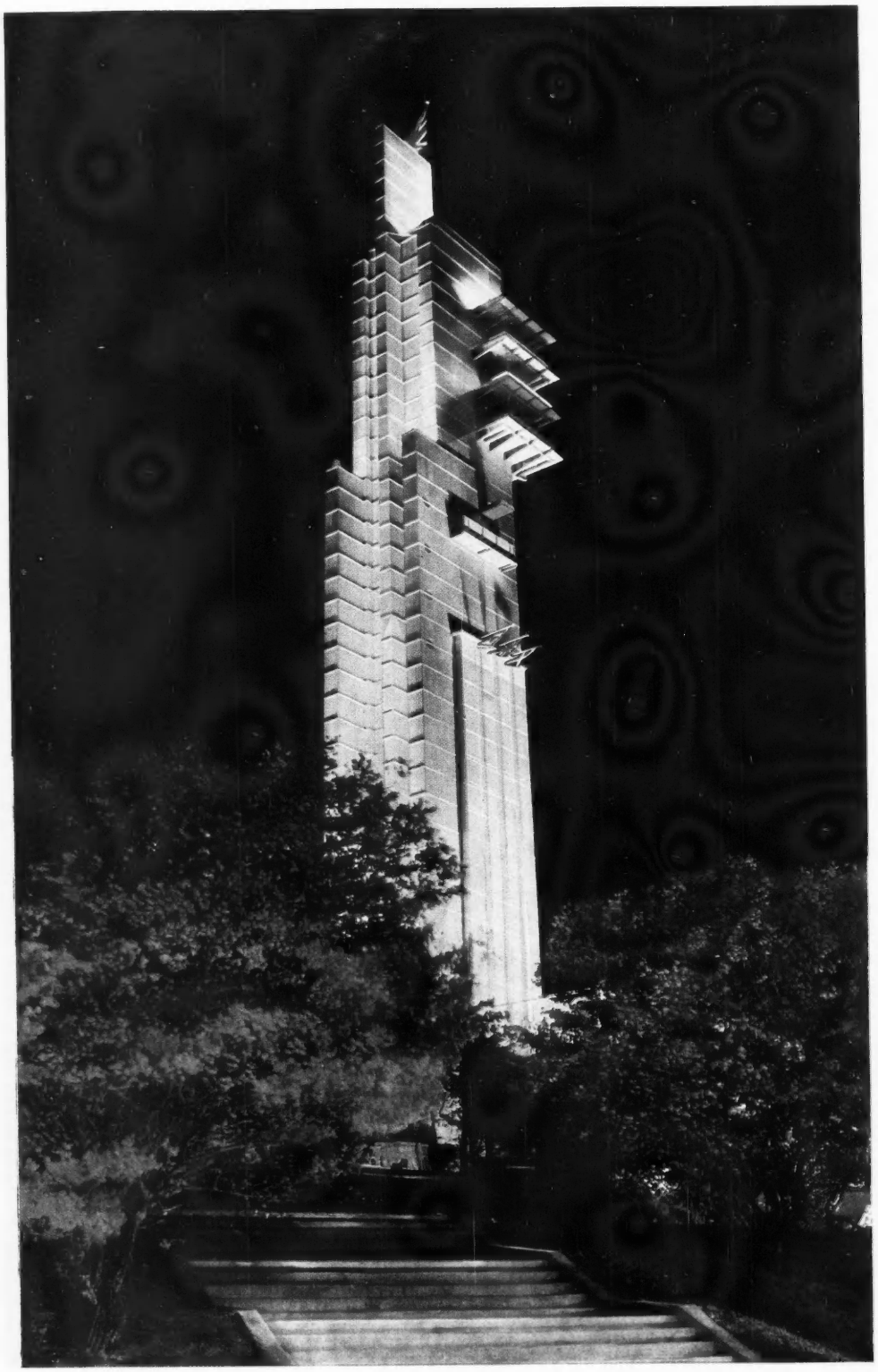

FLOODLIGHTED VIEW OF TAIT'S TOWER ON THE HILL TOP AT THE EMPIRE EXHIBITION, BELLAHOUSTON PARK, GLASGOW.

This structure, situated on the top of a hill, is finished in aluminium and is floodlighted at night by means of tungsten floodlights, while high up on three sides projecting balconies are outlined in broad coloured bands of red, gold and blue obtained by electric discharge colour floodlighting lamps.

G.E.C. Journal

VOL. IX. AUGUST, 1938 No. 3.

Fluorescent Tube Lighting.

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INTRODUCTION.

A SATISFACTORY light for general interior use must first and foremost render the colour of the human skin in a pleasing manner. For what might be termed "recreational" lighting there is a decided preference for a rather warm light, and it is found that, even with a source as rich in red as is the tungsten filament lamp, it is a frequent practice to use a pink or amber tinted fitting to increase the warmth of the light. For the lighting of stores and showrooms, on the other hand, there is a demand for a colder form of lighting which will render the colour of fabrics and objects with reasonable accuracy.

High voltage fluorescent tubes possess many advantages over the more usual filament lamps for both these forms of lighting. The large range of

Fig. 1.—A combination of fluorescent discharge tubes and incandescent lamp fittings in a hotel ballroom.

beautiful pastel colours and the high luminous efficiencies of these tubes have made them eminently suited for practically every type of lighting.

In these tubes the fluorescent powders are applied in the form of thin layers to the inside surface of the tubes. The ultra violet radiation emitted by the discharge is absorbed by the layer of powder and transformed into fluorescent light. The latter mixes with the light from the discharge giving a resultant light of characteristic colour. In certain cases considerably more light is emitted for a given wattage dissipated than is the case when no fluorescent coating is used. In other words, the luminous efficiency of the source is considerably enhanced due to the conversion of the otherwise wasted ultra violet radiation into useful light.

Fig. 2.—Malden Manor Station on the Southern Railway illuminated by a double line of tubing over each platform.

It is not necessary in general to use glass fittings with high voltage discharge tubes to tint the light since they generate light of the colour required and form their own fitting. Furthermore, owing to the low surface brightness of the tubes, it is not necessary to employ any diffusing glass. It is thus possible to make full use of the high efficiency of the tubes while the long tubular lamps enable very good light distribution to be obtained.

In this article the authors have attempted to give a general account of the new form of lighting by means of Osira Fluorescent Tubing. No attempt has been made to describe the highly technical processes involved in the manufacture of the tubes themselves or the extensive tests which have to be made to obtain reliable life and lumen maintenance data. A new development in the method of operating lighting units is described. This method depends upon the use of two small tightly wound high voltage transformers and a separate current limiting device, in place of the usual large leakage reactance transformer. The high voltage components may thus be made sufficiently small to go into electrode boxes of reasonable dimensions. This advantageous method of operating high voltage tubes, which has been patented[1], has been tried successfully on experimental installations.

HISTORICAL.

The electric discharge in gases was proposed as an illuminant as long ago as 1744 by Gottfried Grummert and some years later than this, in 1752, Watson demonstrated a discharge tube almost 3ft. long. This was operated by means of an electrostatic machine and was probably filled with residual air. In the 19th century the works of Davy, Faraday, Plucker, Hittorf and

1. British Patent Application Nos. 5842/37, 10026/37 and 24294/37.

Fig. 3.—Osira fluorescent tube lighting in the flower department of J. Lyons & Co., Ltd., at Coventry Street, London.

Crookes added greatly to our knowledge of the discharge in gases, but little or no practical use was made of the phenomenon until Moore began his researches on the value of discharge tubes as illuminants in 1893. Undoubtedly, however, such a use had long been foreshadowed.

The first installation of electric discharge lighting was erected by Moore at Newark, New Jersey in 1904. This comprised a single tube about 180ft. long operated by means of a high voltage transformer. The success of this installation depended on the use of a special automatic valve for replenishing the gas as it became used up by the action of the discharge. These early tubes of Moore's were filled with air, nitrogen or carbon dioxide.

The discovery early in this century of the group of inert gases, helium, neon, argon, krypton and xenon by Rayleigh, Ramsey and Travers made further developments possible since their relatively low rate of "clean up" rendered the use of a replenishing device unnecessary.

The first long discharge tubes employing a rare gas were made by Claude in 1910. These tubes had a neon filling and their attractive red colour and comparatively high efficiency made them very suitable for advertising and display purposes.

The use of mercury vapour in tubes of a somewhat different type was already known from the work of Arons and Cooper Hewitt and the step of using mercury vapour in conjunction with the rare gases soon followed.

USE OF LUMINESCENT MATERIALS[2].

The use of luminescent powders in discharge tubes may be said to have begun with the work of Becquerel, who experimented with layers of fluorescent powders in discharge tubes as early as 1866. Almost 60 years later Risler proposed to apply the powders to the outside surface of the tubes, presumably to avoid the complications which might be expected to arise through placing the powder in contact with the discharge.

Fig. 5.—An office installation showing Osira fluorescent tubes operated by tandem transformers. The transformers are placed in the electrode boxes.

2. Refer also G.E.C. Journal Vol. VIII., No. 2, May, 1937.

Fig. 4.—Three-colour dimmer controlled cornice lighting employing Osira fluorescent tubes, at the Royal Star Hotel, Maidstone.

The first attempt to use fluorescent powders in high voltage tubes was made in this country by Messrs. Claude General Neon Lights Ltd. in 1933, using the method described below.

The inside surface of the tube is coated with an exceedingly thin film of a suitable binding material by forcing a wet sponge through the tubes by means of compressed air. A thin homogeneous coating of the luminescent material is formed on the tube simply by pouring the powder on top of the layer of binding material.

The gas filling employed with these coated tubes was invariably mercury in Argon or mercury in Argon plus Neon, the discharge through which is particularly rich in ultra violet radiation. The powders used were the relatively inefficient

sulphides, and although these powders have been in recent years almost completely superseded by the much more efficient silicates and tungstates, they nevertheless enabled a large range of pastel colours to be obtained which proved of considerable importance in advertising and decorative lighting.

The fluorescent silicates and tungstates referred to above were described fully in these pages by J. T. Randall[3] and more recently J. W. Ryde[4] has dealt with the application of these and other luminescent materials to light sources. They comprise an exceedingly important class of luminescent material which differ from the sulphides in several important respects, but particularly in being very responsive to short wave length ultra violet radiation. Since a large proportion of the energy radiated by the low pressure mercury vapour discharge is of short wave length, much higher luminous efficiencies are obtained with silicates and tungstates than with sulphides. Thus a high voltage tube coated with a green fluorescing sulphide gives about 15 lumens per watt while in the case of a silicate giving approximately the same colour, efficiencies of 50 to 60 lumens per watt are regularly obtained. Much higher efficiencies than these have been obtained under laboratory conditions.

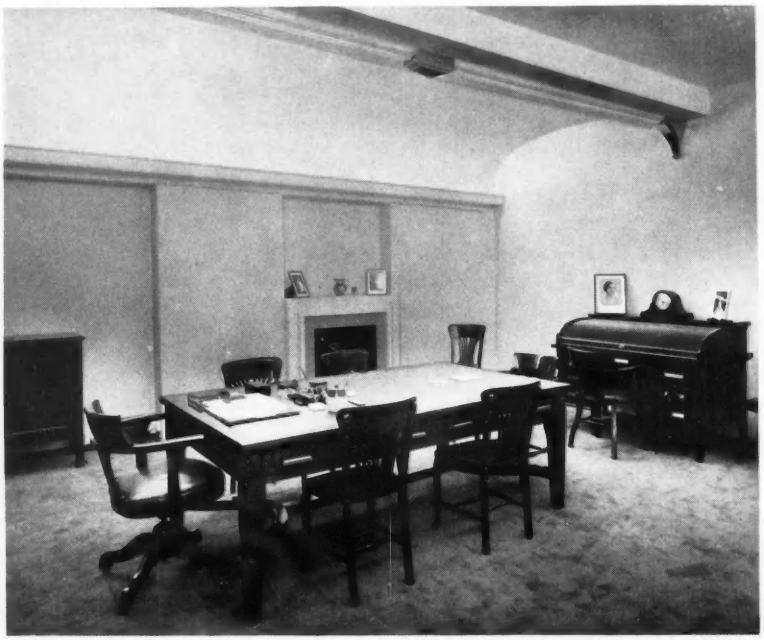

Fig. 6.—A board room in which both direct and indirect fluorescent tube lighting are employed to very good effect.

EXCITATION OF LUMINESCENCE BY THE NEON DISCHARGE.

Until a few years ago the only discharge used for exciting fluorescent powders in positive column discharge tubes was that through mercury vapour. Early in 1935 however, H. G. Jenkins[5] at the G.E.C. Research Laboratories, Wembley, found that both zinc ortho-silicate and calcium tungstate could be strongly excited by a discharge in pure neon. The neon radiations chiefly responsible for exciting the luminescence are the powerful series of resonance lines commencing at 735 and 744 Angstrom Units respectively.

Since these lines represent only about 10 per cent of the total radiated energy in the neon discharge it could hardly be expected that the step up in efficiency with neon would be as great as with low pressure mercury, where some 80 per cent of the total radiated energy is in the ultra violet and is available for exciting fluorescence. On the other hand, the high initial efficiencies of coated mercury tubes fall off to some extent during life, due to the action of mercury vapour on the powder. No such fall off has been observed in neon fluorescent tubes and the initial efficiency is unchanged even after the tubes have been burning for many thousands of hours. The perfect lumen maintenance and abundance of red light in neon fluourescent tubes are, of course, of great importance in connection with interior lighting. Zinc ortho-silicate fluoresces green and this combines with the orange red light of the neon to produce a subjective yellow colour. In the same way the blue fluorescent light from calcium tungstate gives a pink colour with neon. Both these colours are exceedingly valuable for interior lighting purposes.

3. G.E.C. Journal, Vol. VIII, No. 2, May, 1937.
4. Lecture delivered before the I.E.S., 12th April, 1938.
5. British Patent No. 457486.

PHOTOMETRY OF OSIRA FLUORESCENT TUBES.

The use of high voltage tubes for lighting purposes has made the development of accurate methods for measuring the luminous efficiency of these coloured sources a matter of outstanding importance. The difficulties inherent in the photometry of coloured discharge lamps and the methods developed to overcome them have been described already in these pages.[6]

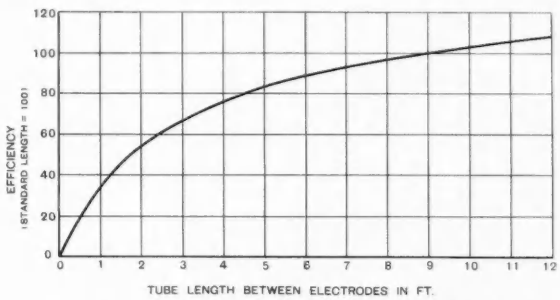

Fig. 7.—Variation of efficiency with length for 20 m.m. diameter mercury filled tubes.

High voltage discharge lamps present their own special problems since the size of the source makes measurements in an integrating sphere very difficult and the relatively low brightness of the tubes makes measurements on a normal photometer bench far from easy. It may therefore be of interest to give a short description of the technique employed at the G.E.C. Research Laboratories when making commercial measurements on the output of these tubes. Two methods are used (*a*) visual comparison "minimum colour difference" method, and (*b*) photo-electric method.

In method (*a*) the directional candle power of a short section of the tube is measured on a horizontal photometer bench, using a contrast or equality of brightness 2 degree field, Lummer Brodhun photometer head. A suitably selected colour filter is placed between the tungsten filament comparison lamp and the photometer head in order to reduce the colour difference to a minimum, the integral transmission of the filter to the light from the tungsten lamp being calculated from its spectral transmission and the internationally agreed visibility data. The distance of the sources from the photometer head is then adjusted in the usual manner until the two sides of the photometer field appear equally bright.

The photometer is calibrated by removing the colour filter and substituting for the discharge lamp, tungsten filament directional standard lamps. These are balanced in turn against the comparison lamp and an instrument constant calculated from the mean results obtained with the group of standard lamps. The candle power of the discharge lamps is readily estimated from the instrument constant so obtained, multiplied by the integral transmission of the particular filter used.

Having determined the candle power of the short section of tubing under consideration in a direction perpendicular to the axis of the tube, the value for the whole length of the tube may readily be found. The luminous efficiency of the tube in lumens per watt is determined by means of the following expression:—

$$\frac{L}{W} = \frac{4\pi C F_1}{E_l I F_2}$$

where $\frac{L}{W}$ = Efficiency of the tube in lumens per watt.

C = Directional candle power of the tube.

F_1 = Ratio of spherical to directional candle power for the particular tube.

E_l = Operating voltage of the tube.

I = Tube current in amps.

F_2 = Wave distortion factor.

For straight tubes with a neon filling F_1 is practically equal to unity, while for mercury tubes, its value is about 0·8. The wave distortion factor for both types of tube is approximately 0·9.

The efficiency is a function of the length of the tube and in the case of Osira fluorescent tubes luminous efficiency data is always given in terms of a tube 9 ft. long. In practice, of course, tubes of various lengths have to be measured, and the result expressed in terms of the standard length. If E_{l_1} and E_{l_2} are the operating voltages of two similar

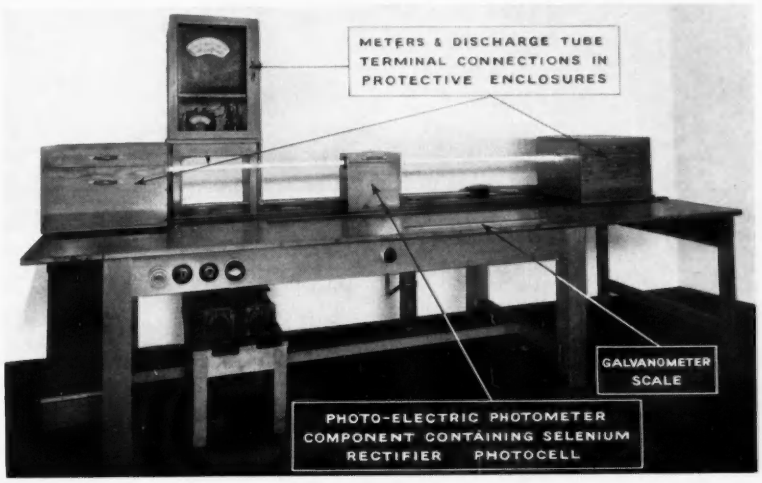
METERS & DISCHARGE TUBE TERMINAL CONNECTIONS IN PROTECTIVE ENCLOSURES
GALVANOMETER SCALE
PHOTO-ELECTRIC PHOTOMETER COMPONENT CONTAINING SELENIUM RECTIFIER PHOTOCELL

Fig. 8.—Apparatus in use at the G.E.C. Research Laboratories for the photometric measurement of high voltage tubes.

6. G.E.C. Journal, Vol. IV, No. 1, February, 1933.
" " Vol. V, No. 3, August, 1934.

tubes of lengths l_1 and l_2 then

$$E_{l_1} = V_e + l_1 V$$
$$E_{l_2} = V_e + l_2 V$$

where V_e = voltage drop at the cathode,
and V = voltage per foot length of positive column.

These equations may be written in the form

$$E_{l_2} = \left\{(E_{l_1} - V_e) + \frac{l_1}{l_2}\right\} + V_e$$

an expression which enables the running voltage of any length l_1 to be determined from measurements

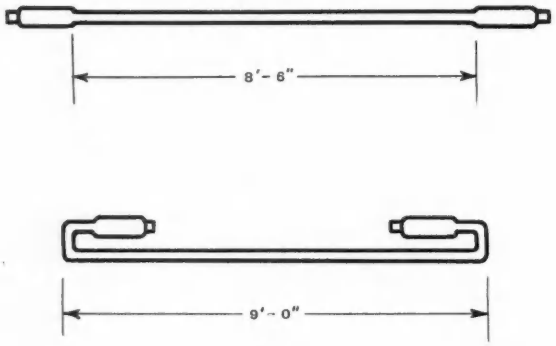

Fig. 9.—Standard lengths of tubes with alternative arrangements of electrodes.

on a length l_2, providing the cathode fall V_e is known. The latter may readily be measured for any given type of tube and generally lies between 150 and 250 volts. The curve in fig. 7 shows how the luminous efficiency of an Osira fluorescent mercury filled tube varies with the length.

For the routine photometry of Osira fluorescent tubes a photo-electric method is largely employed in which a cell of the Selenium rectifier type is used in conjunction with a sensitive galvanometer to measure the light output from a unit length of the tube. This is converted into directional candles by means of a calibration curve obtained for the particular colour under consideration, by measuring a number of tubes of the same colour both visually and photo-electrically. The readings are checked regularly by the visual method to avoid the possibility of errors creeping in, and a further check is obtained by means of a set of standard tubes of each colour.

Fig. 8 shows a photograph of the photo-electric photometer in use at the Research Laboratories for the measurement of high voltage tubes.

The following table gives the average initial luminous efficiency and surface brightness for the more important colours of Osira fluorescent tubes.

TABLE I.

Tube No.	Colour.	Gas Filling.	Tube Efficiency (Initial) in Lumens per watt.	Surface Brightness of tube in candles per sq. in.
—	Orange Red ..	Ne	15	0·9
102	Pink	,,	15	0·9
103	Gold	,,	22	1·23
21	Dark Green ..	ArNeHg	35	1·62
22	Bright Green ..	,,	55	2·58
24	Off White ..	,,	25	1·16
27	Ivory White ..	,,	44	2·07
29	Deep Blue ..	,,	15	0·71
30	Peach	,,	27	1·23
31	Apricot ..	,,	30	1·42
33	Sky Blue ..	,,	30	1·42

Notes.

(a) Efficiencies refer to 20 mm tubes 9 feet long operated at 60 m.a.
(b) For comparison with the above figures a plain mercury tube without coating has an efficiency of only 5 L/W., and a brightness of 0·32 candles per sq. in.
(c) All the tubes are coated except the orange red which is a plain neon tube.

HIGH VOLTAGE LIGHTING UNITS.

The standard straight length of Osira fluorescent tubing has a visible length of 8ft. 6in. when the electrodes are in line with the tube, or 9ft. long when the electrodes are turned back behind the tube. These two arrangements are illustrated in fig. 9.

Although tubes can be made shorter or curved to conform with particular architectural features, lighting schemes are usually designed to employ standard lengths wherever possible. As shown above, the luminous efficiency increases with the length of the tube, but it will be seen from the curve that no great advantage is gained by using lengths greater than about 9ft., while these very long tubes would require greater care in handling and would be more liable to breakage in transit. The electrical characteristics of standard 9ft. tubes are given in Table II.

TABLE II.

Electrical Characteristics of Standard Lengths
(Tubes 9 feet long 20 mm. in diameter).

Filling	Current m.a.	Running Volts	Tube Watts.
ArNeHg	60	790	43
Ne	60	1040	56

In the majority of installations it is desirable to control each colour independently; consequently separate transformers are provided for different coloured tubes. Typical circuits showing the arrangement of tubes and transformers for standard units are given in fig. 10.

Tubes of the same colour are normally connected in series with one another and it is usual to interconnect up to six mercury or four neon filled tubes on one transformer. Where, however, the units are more than a few feet apart, separate transformers are sometimes used for each unit to avoid long lengths of high tension series cable.

In order to secure a resultant light suitable for general purposes two or more of the colours in Table I are used in combination. In certain cases, and particularly where the discharge lighting is supplementary to existing filament lamp lighting, it is possible to use some of the colours in Table I singly with very good effect.

In the case of visible units a symmetrical arrangement of the tube is desirable and the usual arrangement comprises three tubes disposed in a horizontal plane with their axes parallel and spaced about one inch apart. The two outer tubes are of one colour—red for example—while the central tube is of a different colour—such as green. The appearance of a unit of this type may be improved by placing the central tube inside a frosted envelope about 45 mm. in diameter. In the case of tubes used in coves or cornices, a symmetrical arrangement of the tubes is not essential, and in these cases a frosted outer envelope would serve no useful purpose.

The different colours which comprise the units must, of course, be mixed in certain ratios. The optimum resultant colour is found by careful tests in which particular attention is directed to the appearance of the human skin and the colour rendering of fabrics and objects.

Table III gives photometric and electrical data for a number of standard lighting units.

The lumen values given are the average figures during a period of 4000 burning hours.

The high tension wiring outside the electrode boxes is made with special metal shielded cable. The metal shielding, which is earthed, acts as one plate of a condenser connected between earth and the high tension wire, the wire itself acting as the other plate. Fig. 11 shows the equivalent circuit in which the self capacity of the cables is represented by two condensers, C_1 and C_2 connected in series across the tube. If the lengths of cable used are increased, C_1 and C_2 also increase until a point is reached where resonance conditions may arise. In these circumstances the normal operation of the tube may be impaired and transformer failures are liable to occur owing to the excessive resonance voltages set up. It is thus necessary to keep the lengths of high tension cable, and hence the capacities as small as possible.

Before installing a high voltage lighting unit it is

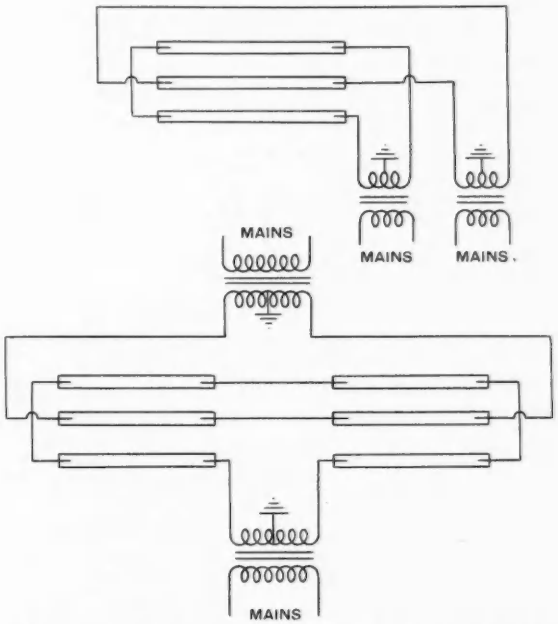

Fig. 10.—Typical circuit arrangements for single and double units.

TABLE III.

Combination Letter	A	F	G	H	J	K	L	M	N	O
Arrangement of Tubes	Red — Green 22 Red —	Red — Green 21 Blue 29	White 24 Pink 102 White 24	White 24 Gold 103 White 24	Peach 30 Sky Blue 33 Peach 30	Peach 30 Sky Blue 33 Peach 30	Sky Blue 33 Gold 103 Sky Blue 33	Sky Blue 33 Pink 102 Sky Blue 33	Gold 103 White 24 Sky Blue 33	Peach 30 Gold 103 Peach 30
Overall Watts (Initial)	120	Adjustable over wide range	115	115	110	120	115	115	115	130
Total Lumens	2760		2070	2300	2750	3000	2760	2530	2530	2860
Overall Lumens per Watt (Initial)	23		18	20	25	25	24	22	22	22
Resultant Colour	Warm		Somewhat warmer than Daylight	Near Daylight	Very close to Daylight	Warmer than Daylight	Near Daylight	Warmer than Daylight	Near Daylight	Warm

Only triple tube units have been considered in the above table. In certain cases it is possible by adjustment of the tube currents to get satisfactory resultant lighting from units comprising only two tubes.

INSTALLATION.

The British Standards Institution clearly defines the requirements necessary for the manufacture and installation of electric discharge tubing, and all high voltage lighting installations should comply with these conditions. The electrodes at the ends of the tubes are completely enclosed and protected by metal electrode boxes. Each box is fitted with insulated clips to support the tubes and ample clearance is provided between electrodes and earthed metal to prevent the possibility of brush discharge. It is essential that metal electrode boxes and other exposed metal parts should be efficiently earthed.

necessary to arrange for transformer accommodation and high voltage cable runs.

For the reasons given it is highly desirable that the transformers should be located as close to the unit as practicable, in order to keep the lengths of high tension cable as short as possible. When a false ceiling exists it is often convenient to house the

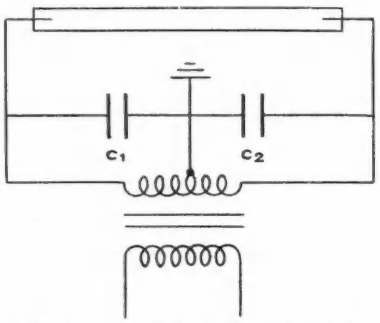

Fig. 11.—Capacity effect of metal shielded cables.

transformers in the space above. In this case suitable facilities must be provided for periodic inspection.

The provision of adequate ventilation for the transformers is necessary in order to prevent overheating. In cases when other positions have to be found and where there is a possibility of the transformers being accessible to unauthorised persons, well ventilated locked metal or teak enclosures are advisable.

The high voltage wiring is carried out with single core cables insulated with vulcanised india-rubber and having an outer layer of ozone-resisting compound. For the majority of installations the cables are lead covered, but when installed in positions where they may suffer mechanical damage, armoured cables are used or the lead covered cable is protected by metal channelling. It is undesirable to draw lead covered high tension cable through steel conduit owing to the danger of mechanical damage. For the same reason sharp bends in the cable must be avoided.

There is usually little difficulty in making arrangements for the wiring when a building is in course of erection, but more consideration is invariably required where units have to be installed in existing buildings. The most suitable position for the cables is immediately above the ceiling if an accessible space is available, but if a cable way cannot be provided above the ceiling, the wiring must be recessed into a channel chased out of the ceiling, or else surface wiring must be adopted. Lead covered high tension cable should never be buried in plaster unless armoured.

All high voltage discharge tube installations are controlled on the primary side of the transformers. The I.E.E. Regulations for the Electrical Equipment of Buildings stipulate separate cut-outs to protect each transformer. The size of the distribution board required will, therefore, be determined by the number of transformers. When groups of tubes are to be controlled independently, a distribution board with split bus-bars can be used, or, alternatively, a board for each group of tubes with separate switches controlling each board.

In addition to the local control switches, the main incoming supply to all installations must be controlled by a "locked" switch arranged to open and close the circuit on all poles. Specially constructed switches are available, fitted with a key which may be removed only when the switch is in the "off" position. The switch cannot be closed until the key is replaced. Before working on the installation the maintenance engineer removes the key which he retains until work on the installation is finished. In small installations the "locked" switch usually controls the supply to the main distribution board feeding the sub-boards or transformers. In larger installations, however, it is preferable to insert a contactor in the main input and to control the operating coil of the contactor by means of the "locked" switch.

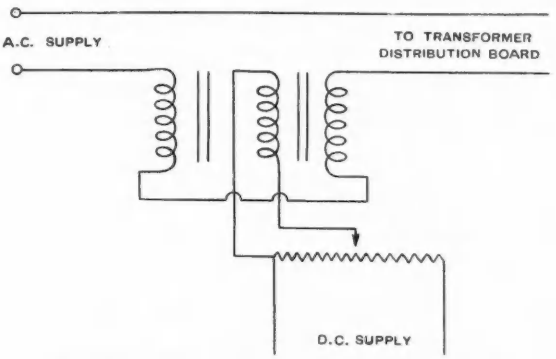

Fig. 12.—Typical circuit arrangement in which a single choke is used to control a number of transformers simultaneously.

COLOUR CONTROL.

The intensity of the light from high voltage electric discharge tubes can be readily controlled by means of the tube current. In most cases the tube current (and therefore the light output) may be varied over a wide range without changing the colour of the light to any serious degree. The colour of the resultant light from two or more differently coloured tubes may, however, be varied widely by varying the current through the different tubes.

Colour control is equally important whether it is desired to obtain changing colour effects or to maintain a fixed colour throughout life. Where it is desired to obtain changing colour effects, red, blue and green tubes are usually used in a system of indirect lighting. This combination of tubes enables a very wide range of colour effects to be obtained. Each colour is con-

trolled independently or "dimmed" by one of the following methods :—

(1) Resistance in primary circuit.

(2) Choke in primary circuit.

Method (1) has the advantage of being comparatively inexpensive and is particularly suitable for small installations. With this system of control the wattage consumption of the circuit remains practically constant when the intensity is reduced from maximum to minimum. In the latter condition practically all the energy is being dissipated by the resistance, which must, therefore, be adequately ventilated to prevent overheating.

In the second method of dimming by means of chokes very little energy is absorbed by the choke and the wattage consumed depends on the light output.

The most usual method of varying the impedence of chokes used for dimming purposes is by direct current saturation of the core. A typical circuit arrangement in which a single choke is used to control a number of transformers simultaneously, is shown in fig. 12. The choke is constructed with three coils. The outer coils are interconnected and wired in series with the supply to the transformers. The central coil is connected to a direct current supply, which is generally obtained from a rectifier. The effect of passing a direct current through the central coil is to produce magnetic saturation of the core, thus reducing the effective inductance of the choke and increasing the current through the tubes.

It is not in general possible to dim high voltage tubes to complete extinction owing to the development of flicker at very low currents. Mercury tubes may be dimmed down to about 10 per cent of their maximum or lower, while in the case of tubes with a neon filling the intensity can be reduced until approximately 20 per cent of the initial light remains. This degree of dimming is found to be sufficient for most purposes.

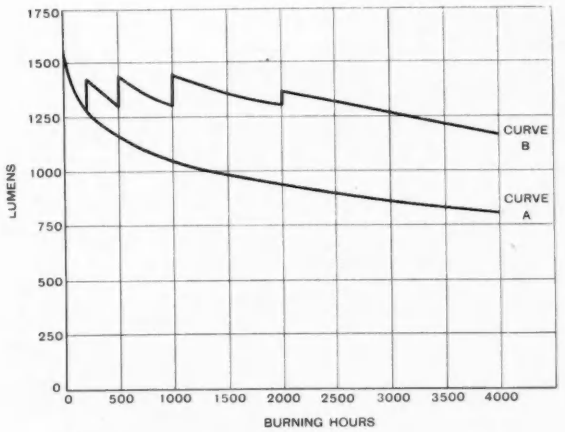

Fig. 13.—Luminous output of mercury filled tube with and without variable choke.

As stated earlier in this article the light output of fluorescent tubes using a mercury filling tends to fall off during life. This is not the case with fluorescent tubes using a neon filling, so that in lighting units employing both types of tubes the initial colour balance changes as life proceeds, unless steps are taken to compensate for the fall off of the mercury filled tube. The tendency is for the resultant light to become somewhat warmer as life proceeds and although in many cases this may not be in the least objectionable, other cases arise where it is important to maintain the original colour throughout life. A special choke has been developed to enable adjustments in the current passed by the mercury tubes to be made at stated intervals throughout life, thus ensuring that the lumen output of these tubes will remain approximately constant. An hour meter is a convenient means of ensuring that the current adjustments are made at the stated times.

In fig. 13, curve A shows how the light output of a typical mercury filled fluorescent tube falls off if no adjustment is made in the current throughout life. Curve B shows how, by adjusting the current through the tube at the stated times, the light output may be rendered approximately constant.

TRANSFORMERS AND POWER FACTOR.

When an increasing voltage is applied to the electrodes of a discharge tube current only begins to flow when the voltage reaches a certain value known as the striking voltage of the tube. The passage of current through the tube is accompanied by the characteristic glow of the gas filling and the brightness of the glow in most cases increases with the increasing current. Once the current has begun to flow it tends to rise to a very large value unless some form of current limiting device, such as a choke or resistance, is employed.

When the current through the tube is limited to a given value by a choke or resistance, the voltage across the electrodes (the running voltage) is found to be considerably less than that required to "strike" the discharge. In the case of tubes of the type used for interior lighting the ratio of striking to running voltage lies between 1·5 and 2·0.

The most convenient method of obtaining the voltage necessary for the operation of high tension tubes is by means of step-up transformers of the leakage reactance type. A typical current-voltage characteristic for one of these transformers is shown in fig. 14.

This provides just the right characteristic for operating the tube. The high open circuit voltage V_s "strikes" the discharge and as soon as current begins to pass the voltage falls to a value V_R while the current increases to a value I_T not much below the short circuit current of the transformer.

Transformers are enclosed in lead coated sheet steel cases filled with compound and are completely weather-proof. It is thus possible to place the transformers in the open outside the building when

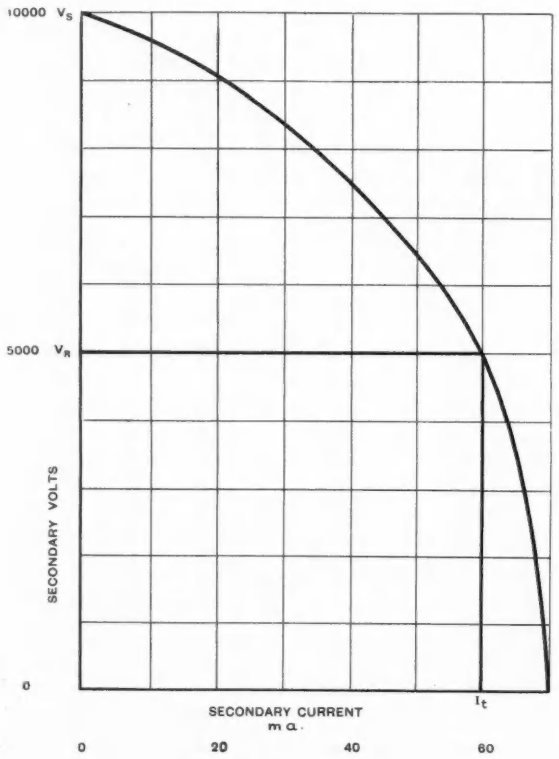

Fig. 14.—Leakage reactance transformer characteristic.

suitable indoor accommodation cannot be found. It is usual to provide a number of tappings on the primary winding to permit adjustment of the output voltage, should this be necessary.

As might be expected the use of a choke or leakage reactance transformer leads to a rather low power factor. This may be corrected to about 0·85 where necessary by means of condensers connected across the supply. Correction to unity is possible but is not done in practice since it involves the use of special circuit arrangements.

In the case of an installation comprising a number of separately controlled circuits the power factor of each circuit is corrected independently. If a single bank of condensers were used for the complete installation, in the event of only part of the installation being in use, over correction would occur, with resulting reduced power factor. The capacity of the condensers required to correct the power factor of an installation may be calculated from the following expression :—

$$C = \frac{W \times 10^6}{2\pi f V^2} (tan\ \phi_1 - tan\ \phi_2)$$

where C = capacity of condenser in microfarads.
W = load in watts.
f = frequency of the supply.
V = voltage of the supply.
ϕ_1 = phase angle without condensers.
ϕ_2 = phase angle with condensers.

NOTE : Power Factor without condenser = $cos\ \phi_1$
Power Factor with condenser = $cos\ \phi_2$

Assuming that the uncorrected power factor ($cos\ \phi_1$) is 0·37 and the final power factor ($cos\ \phi_2$) is 0·85 then in the case of a 50 cycle supply the above expression simplifies to :—

$$C = 2230 \frac{I}{V_m}$$

where I = primary current before correction.
and V_m = the supply voltage.

TYPICAL INSTALLATIONS.

High voltage discharge tubes have a wide field of application for interior illumination and are equally suitable for providing direct, semi-indirect and totally indirect lighting. The accompanying illustrations give some idea of the variety of installations which have been carried out using Osira fluorescent

Fig. 15.—Excellent colour rendering and uniform light distribution are obtained in this store which is lighted entirely by Osira fluorescent tubing.

tubes. In many cases the problem consists of providing a warm quality of light, while in other cases a light which is a close approximation to daylight is called for. General details are given here of some typical installations.

A store illuminated entirely by electric discharge tubing consisting of triple tube units is shown in fig. 15. The tubes follow the layout of the counters and provide an average intensity at counter level of 15 foot candles with a diversity which reduces the intensity by less than 1 foot candle between counters. The combination of tubes used comprises white, blue and gold tubes and gives an excellent colour rendering.

The advantages of cornice lighting have long been appreciated, but it was not until fluorescent tubes were introduced into the lighting field that this form of illumination with flexibility of colour control could be obtained at an economical running cost.

Triple tubing, consisting of red, green and blue tubes, are usually employed for indirect lighting schemes when colour changing is required.

Fig. 16.—A general view of the Electricity Showrooms in the new Manchester City Hall extensions. Three-colour indirect lighting is provided by 3,500ft. of Osira fluorescent tubing.

An interesting example of this type of lighting is illustrated in fig. 16. Each colour is separately controlled by a motor driven dimmer which is operated from a push button control panel. An infinite number of colour effects is obtained by mixing the component colours in varying proportions.

The increasing importance of accuracy in the production of equipment, such as aeroplane engines, calls for extreme care and precision in checking

Fig. 17.—Electric discharge tubing installed in the gauge standards room of an aeroplane engine factory.

patterns with master patterns. A number of factories are now equipped with specially constructed gauge rooms which are air conditioned, and maintained at a constant temperature. These rooms must be provided with a light of high intensity, good diffusion, and accompanied by a minimum heat dissipation. It is particularly important to avoid local regions of high temperature and for this reason the use of local lighting by filament lamps is out of the question.

Pink and white tubes are installed in the gauge room illustrated in fig. 17, and provide an ideal quality of light with an average intensity of nearly 30 foot candles on the working plane, about 8ft. from the tubes.

The lighting of the wireless receiving room of the Cunard-White Star liner "Queen Mary" presented a number of problems with which the illuminating engineer frequently has to contend.

This room has a low ceiling and is entirely dependent upon artificial illumination. The exacting nature of the work of the wireless operators calls for a quality of light as natural as possible. In an attempt to produce a daylight effect the ordinary incandescent tungsten filament lamps were replaced by daylight blue lamps with the result shown in fig. 18. It should be absolute freedom from any form of wireless interference in the wireless room. The ship's transmission and reception wave lengths cover a range between 17 metres and 18,000 metres, and exhaustive tests made since the installation was completed have failed to reveal any wireless interference.

Fig. 18.—The wireless receiving room of R.M.S. "Queen Mary," as originally illuminated by 60 watt daylight blue lamps. This illustration should be compared with fig. 19.

be mentioned that the lamps were enclosed in white opal spherical fittings which reduced the glare to some extent, but a low intensity and a very poor diversity were obtained. Working under these conditions was found to be extremely difficult. The old form of lighting was replaced by an installation of Osira fluorescent tubing comprising 4 units each 8ft. 6ins. long.

Fig. 19 is a photograph taken with the room illuminated by the tubes. Their large surface area provides a uniform intensity on both the vertical and horizontal planes of the order of 12 foot candles as compared with 2 foot candles from the daylight blue lamps; the wattage consumption remains practically unchanged. The quality of light might be described as a close approximation to sunlight.

It was of course imperative that there should

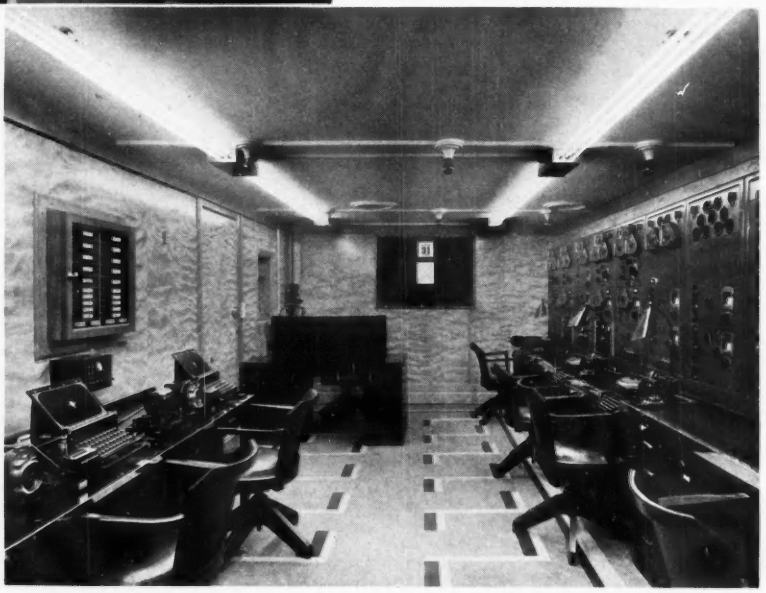

Fig. 19.—A striking contrast to fig. 18, showing absence of shadows and higher intensity obtained without any increase in power consumption from two lines of Osira fluorescent triple tubing.

TANDEM TRANSFORMERS.

A New Development.

A new method of operating high voltage tubes which is likely to prove of considerable importance for interior lighting has been developed at the G.E.C. Research Laboratories. In this the usual double wound leakage reactance transformer is replaced by two tightly wound auto-transformers, one at each end of the tube load and connected so that their secondary voltages are 180° out of phase. In order to limit the current through the tubes to the desired value some form of current limiting device, such as a choke, must be used. Furthermore, in order to comply with the B.S.I. recommendations for luminous discharge tube installations it is necessary to isolate the high voltage auto-transformers from the mains. Both these requirements are met by the use of a 1 to 1 ratio double wound leakage reactance transformer

as the current limiting device. The primary of the transformer is connected to the mains supply, while the secondary is connected in series with the primaries of the auto-transformers. The circuit is shown in fig. 20.

The use of an isolation transformer also enables one point on each high voltage winding to be joined to earth as required by the B.S.I. specification referred

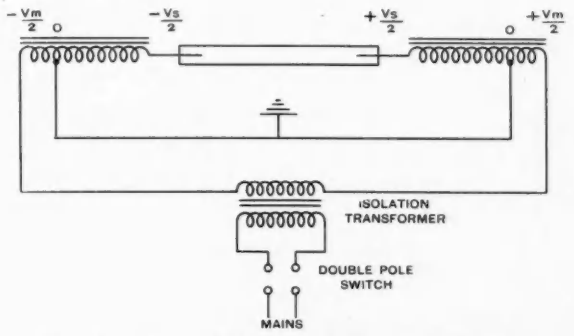

Fig. 20.—Two auto-transformers used in tandem.

to above. If the open circuit potential required to operate the tube load is V_s then each auto-transformer is wound to give an open circuit voltage of $\frac{V_s}{2}$

The advantage of this arrangement is that the high voltage transformers may be made small enough for one to go into each electrode box at the ends of the lighting unit. Direct connection inside the box may then be made to the tube and all external high voltage wiring thereby eliminated. The circuit shown in fig. 20 may be used for several tubes connected in series. The tubes may be in line or arranged with their axes parallel, as in the case of the standard three tube units.

The circuit described above overcomes two major difficulties in the installation of high voltage lighting units; firstly, the positioning of the transformers, and secondly, the use of metal shielded high tension cable. On the other hand, it suffers from the disadvantage that with units employing both neon and mercury filled tube, it is not possible to control the colour during life, since all the tubes are in series. Certain combinations of tubing are less susceptible to colour change than others and, with these, inability to control the lumen ratio is not a serious factor.

High voltage tubes fitted with hot cathode electrodes are being used by Claude General Neon Lights, Ltd., for certain high intensity signs. Tubes of this type are also being used in the G.E.C. Research Laboratories for experimental interior lighting installations.

Fig. 21 shows how the auto-transformers may be applied to operate a tube fitted with directly heated hot cathode electrode.

In this a few extra turns of heavier gauge wire are added to the free end of the secondary, thus

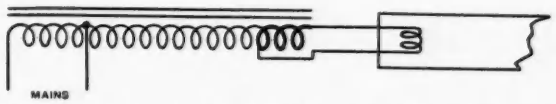

Fig. 21.—Auto-transformer with filament heating coil.

providing a filament heating current. When the supply is first switched on full filament heater voltage is obtained and the filaments glow brightly, thus facilitating starting. When the tube strikes the heater voltage falls to about half this value and the filaments run much cooler.

Clearly, if the above arrangement is applied to more than one tube connected in series, a separate filament heating transformer must be employed for each pair of adjacent cathodes remote from the auto-transformer. Another method of operating high voltage tubes by means of transformers arranged in tandem is illustrated in fig. 22.

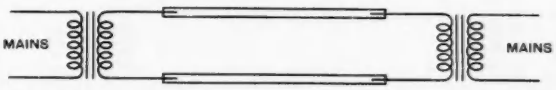

Fig. 22.—Two true-wound transformers used in tandem.

In this, two true wound transformers are used in the manner shown in the figure. A primary choke, which may be variable, is used to limit the tube current to its proper value. The above arrangement may be used for lighting units comprising an even number of tubes. Filament heating windings may be provided as in the previous example.

Although the development just described is relatively new it has been used successfully in a number of small installations. There is little doubt however that the old method employing double wound high voltage transformers will continue to be used for many installations where for various reasons auto-transformers are unsuitable.

High-Power Valves: Construction, Testing, and Operation.

PART I.

By J. BELL, B.Sc., J. W. DAVIES, and B. S. GOSSLING, M.A.

Research and Engineering Staffs of the M.O. Valve Co., Ltd., at the Works, Hammersmith, and (G.E.C.) Research Laboratories, Wembley.

This article is reprinted from the Proceedings of The Institution of Electrical Engineers and was presented as a paper before the Institution in March, 1938.

In the introduction the authors discuss how the development of high-power valves is influenced by the standard of reliability demanded by such services as broadcasting. Subsequently, they describe the principles governing the constructional design, manufacture and function of each main part of the valve.

INTRODUCTION.

THE development of high-power valves is a relatively slow process, so that it is only at intervals of several years that advances can be recorded in any comprehensive fashion. It is actually some 10 years since valves of the particular sort here considered—those made by the M.O. Valve Co.—were described by W. J. Picken to this Institution.[1] This slowness seems in retrospect to have been imposed by the circumstances in which the majority of such valves are used.

For a better understanding of these circumstances the following instances may be cited.

First of all there is the very high standard of reliability demanded by those services of which broadcasting is the type. In these there is no answering back or possibility of repetition, and a brief interruption may affect irrevocably a million listeners instead of merely a few. The standard is comparable with that of power-supply plant, for although there are admittedly frequent opportunities for servicing in the intervals of programmes, there is on the other hand no automatic alternative source of supply, even temporarily. It is not the fact that a valve has failed and has to be replaced that is important; it is that an interruption to the service has occurred. It is a question of operation, not of economics. As a result of this requirement, improvements which may affect performance in operation are generally introduced one at a time, leaving well alone for the time being in other directions. Certain kinds of improvement, *e.g.*, in mechanical construction or characteristics, have latterly been accelerated by preliminary studies using demountable models.

Then there is the long life expected of the valves. This is not the same thing as reliability, for reliability depends chiefly on the absence of premature failures, whereas a long average life has virtues of its own. Apart from the cost of the valves themselves, there would be additional calls on the time of the station staff, and need for more spares at remote stations, if replacements were more frequent. This long life fixes the time unit of the development process at 3 or 4 years, since that is the period generally required to work through the whole of even the first batch of a new type of valve, and so to obtain a first general idea of its overall performance, although the proportion of premature failures, if any, will already have been known after the first few months. Extended life tests of valves of the highest order of power are not feasible, although from time to time manufacturers have recorded their thanks to various authorities for facilities for preliminary operation, which have been of great value in eliminating causes of premature failure. Fortunately, premature failures have been less common in recent types of valve.

Further, none of these large valves is made in very large numbers, so that the picture of overall performance must be statistically crude if there are many points of difference between different types.

Now these operating conditions and requirements which have been enumerated are much the same for all the many types of valve which come within the scope of this paper. In consequence, there are various threads of common practice running through all the several designs, and it is our purpose rather to follow these threads, giving particular instances in illustration, than to go into detailed description of the few types for which space would permit such treatment.*

To economize space by avoiding repetition, the reader is referred from time to time to a general survey of the development of large radio transmitting valves by Le Rossignol and Hall.[2]

1. A reference is given at the end of this article for this and subsequent numbers.

* A table showing the principal ratings for the various types of valve mentioned in the article and for the other high-power types is given at the end of the article.

CONSTRUCTIONAL PRINCIPLES.

(a) General.

The use made of engineering principles in the construction of small valves is largely concealed because these principles are mainly applied to the machines and tools by means of which the valves are made, and they therefore appear only indirectly in the finished valve. A high-power valve, on the other hand, shows itself more directly as an engineering construction. The principles followed are, however, distinctly specialized and must be classed as an extreme case of what may be called high-temperature engineering.

This is for the reason that in many of the parts of the valves the ranges of temperature experienced between idle and operating conditions are wide, and in some cases very wide indeed. Also, under the temporarily more severe conditions of manufacture, they are in general wider still; in fact, they include the widest at present known in engineering.

These temperature ranges imply corresponding expansions, and our experience with these valves has shown that the one overriding rule which must never be violated, if trouble is not to follow, is that the effects of differential expansion must on no account be ignored.

The valve is, of course, also an evacuated high-voltage device, but the requirements arising in these directions have been found to be of relatively minor importance as regards the constructional design.

Throughout the account now to be given, the demands of differential expansion can be seen in the background of the design, whatever part of the valve may be under immediate consideration.

Fig. 1 is a radiograph showing the internal and external construction of a high-power valve, type C.A.T.14; most of the features now to be discussed are indicated in the Figure.

(b) Glass.

The glass envelope or bulb is a convenient starting point for this outline of the principles of construction because in one way or another all the other parts are mounted upon it.

Throughout the development of high-power valves we have continued to use a relatively soft glass. This has served us so well that there has been little incentive to change it, and no change at all has in fact been made. The glass contains a fairly high proportion (30 per cent) of lead, and in consequence it is elastic and withstands "thermal shock," *i.e.*, sudden local expansion, relatively well; it is also viscous over a rather wide range of temperature, does not de-vitrify quickly through chemical instability, and can be fully annealed at a convenient temperature. Further, joints between glass and glass are in no danger of minute pin-hole leaks. These properties form a good basis for somewhat ambitious glass-working operations, such as main glass-to-glass seals 5in. in mean diameter.

Troubles which might arise from electrolysis of hot glass parts have been avoided by substituting potassium for half of the sodium and by adding lead. The proportion of lead is sufficient to absorb X-rays to a useful extent, particularly where, as in these valves, such rays strike glass 2 or 3 mm. thick at glancing incidence. The radiograph, taken at 150 kV peak voltage, illustrates this point.

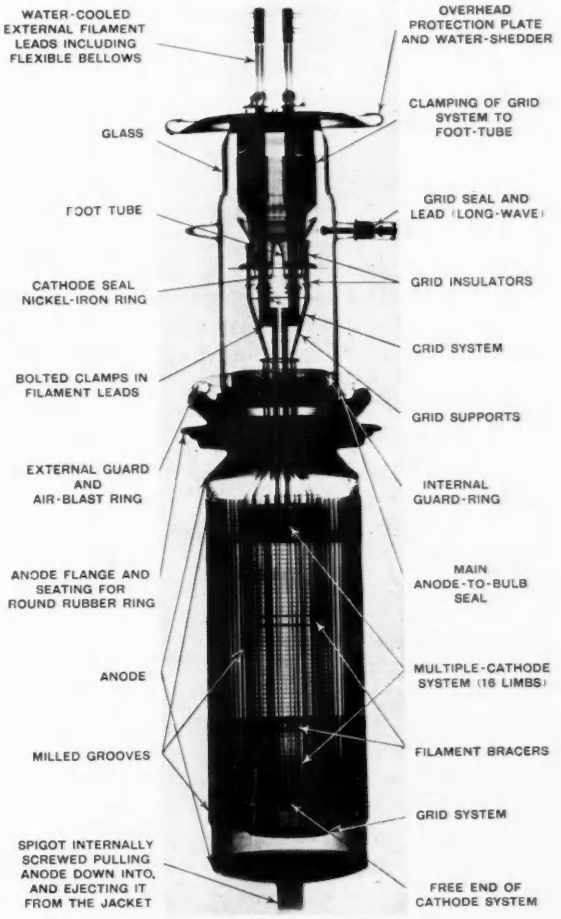
WATER-COOLED EXTERNAL FILAMENT LEADS INCLUDING FLEXIBLE BELLOWS
OVERHEAD PROTECTION PLATE AND WATER-SHEDDER
CLAMPING OF GRID SYSTEM TO FOOT-TUBE
GLASS
FOOT TUBE
GRID SEAL AND LEAD (LONG-WAVE)
CATHODE SEAL NICKEL-IRON RING
GRID INSULATORS
GRID SYSTEM
BOLTED CLAMPS IN FILAMENT LEADS
GRID SUPPORTS
EXTERNAL GUARD AND AIR-BLAST RING
INTERNAL GUARD-RING
ANODE FLANGE AND SEATING FOR ROUND RUBBER RING
MAIN ANODE-TO-BULB SEAL
ANODE
MULTIPLE-CATHODE SYSTEM (16 LIMBS)
MILLED GROOVES
FILAMENT BRACERS
GRID SYSTEM
SPIGOT INTERNALLY SCREWED PULLING ANODE DOWN INTO, AND EJECTING IT FROM THE JACKET
FREE END OF CATHODE SYSTEM

Fig. 1.—Radiograph of a typical high-power valve (type C.A.T.14).

The presence of lead and the low sodium content reduce the high-frequency power factor to a low value, but no use is actually made of this virtue.

The lower softening temperature and higher expansion of this glass as compared with harder glasses of the boro-silicate type are fortunately compensated for by the fact that it absorbs much less low-temperature thermal radiation than those glasses, and is therefore subjected to smaller ranges of temperature during operation of the valves.

The thermal expansion, 9·1 parts per million per deg. C., is probably too great for constructions

involving stout metallic members embedded in thick pieces of glass. However, when the very different elastic properties of metals and glasses in general are taken into consideration, such constructions, whatever appearance of robustness they may present, inspire anxiety rather than confidence, and an anxiety which is renewed with every increase of size.

(c) Anodes.

The material of the anodes is copper of good ordinary quality with a low content of volatile impurities such as arsenic. In the larger valves the anodes are 5in. in diameter and $\frac{3}{16}$in. thick, or 8in. by $\frac{5}{16}$in., these latter being milled to a depth of $\frac{1}{8}$in. in longitudinal grooves $\frac{1}{8}$in. wide so as to double the surface presented to the cooling fluid. To prevent fine leaks exposure of the "end-grain" of the drawn or rolled metal is avoided. Leaks through the copper are very rare.

For soldering the end plates and alloy rings, high-quality silver solder free from volatile impurities is used. Actually, there was more trouble in times long past in making sound vacuum-tight joints between copper and alloy than between alloy and glass; it was found essential to distribute the strains due to differential thermal contraction fairly between the two materials.

It is sometimes found worth while to blacken parts of the inside of anodes with graphite, in order to reduce the furnace effect of the intense cathode radiation and the proportion of such radiation reaching the glass envelope.

These large anodes expand to a notable extent when heated. For a 21in. length the expansion at the "baking temperature" of 400°C. is 0·14in., and at the full-load operating temperature of about 130°C. 0·034in. This latter expansion can be met by using rubber rings of circular section between anode and jacket, but *not* by flat rubber gaskets.

The cooling of anodes will be considered later in this Section.

An internal guard-ring overlapping the seal is inserted into the throat of the anode for the purpose of protecting the seal and the neighbouring part of the glass from cathode radiation, metallic deposits, strong electric fields, and damage from discharges, or electrolysis consequent on direct electron bombardment.

(d) Glass-to-metal seals.

The seal between anode and bulb is the most striking in point of size, but, as we shall see, the same principles apply to the other seals.

Wherever possible a ring of nickel-iron alloy whose expansion is closely matched to that of the glass is interposed between glass and copper. This ring is usually copper-plated, and treated with borax to improve adhesion to the glass. The correctness of the composition of batches of alloy is carefully watched, and all batches are checked for expansion. Given this control, the actual sealing edge need not be thinner than can readily be obtained by simple turning—and the alloy machines quite well—and it can be left with ample strength to resist the atmospheric thrust which for a seal of 5¼in. diameter amounts to 20 lb. per inch of circumference, *i.e.*, more than 300 lb. in all.

The reliability of these seals is unquestionable; failures, whether during manufacture of the valves or afterwards, are extremely rare—a result well worth the few additional operations they require.

Since the glass is applied to the outside only, protection from indentation of the alloy ring is provided in the finished valve. Otherwise there is only one likely cause of fracture. This should be mentioned because it might not be expected. A clean crack round the body of the glass clear of the seal itself can result from a sharp blow on the anode or its supports due, for instance, to sudden contact with a hard object. A similar blow on the glass does not produce this effect.

In cases where the seal is in a strong high-frequency magnetic field which can induce toroidal eddy-currents in it the bare nickel-iron alloy is unsuitable; it overheats to a remarkable degree. To avoid this, either the nickel-iron is copper-plated thickly enough to survive oxidation when the seal is made, or else a direct copper-to-glass seal is substituted. The latter is successfully used up to 5¼in. diameter; it requires close control of the sharpness of the edge combined with sufficient thickness to withstand the atmospheric thrust even when the copper is fully annealed; the glass is usually applied to the inside only.

After experience of both types the ring of intermediate alloy is still preferred wherever there is free choice, except perhaps in small sizes less than $\frac{3}{4}$in. diameter.

(e) Insulation.

The glass envelope itself is the main insulator, but its insulating properties call for little comment. On the outside it is warm and dry, and high-voltage breakdown would occur first in the heated air. The only danger point for electrolytic conduction would be between the filament seals, particularly if a.c. heating is used, but there the temperature is kept low for the sake of the seals themselves.

However, those parts which are subject to high-frequency electric fields can be destructively overheated if their surfaces on the vacuum side are coated, even discontinuously, with a conducting film whose resistance is of the same order as the capacitative impedance of the space round about the film. Since the heating results from the diversion to the film of the displacement current in the space,

this effect is more troublesome in short-wave valves. The formation of such films by volatilization or sputtering of internal metal surfaces during exhaust has therefore to be avoided. High-frequency dielectric losses in the glass itself are completely negligible in comparison with those in such films. The internal guard-ring extension of the anode prevents the formation of films in the stray field close to the anode seal.

Of other insulators besides the envelope there are hardly any. Their presence within the active portion of the valve is nowadays in no circumstances permitted. The combination of some or all of the adverse agencies of high temperature, high voltage, and high frequency, together with film formation, is altogether too hard on them for good reliability to be expected. There is a further less obvious probability which our experience has sufficiently demonstrated in those cases where we have tried to use steadying insulators in such places. This is, that any breakdown of films will result in much more serious breakdown of the vacuum insulation through piloting of flash-arcs—assisted Rocky Point effect.[3]

The grid-cathode insulators, which, if used, are of silica and similar in form to those of ordinary sparking plugs, are therefore withdrawn to a position as far as possible from the active regions, and the cathode system is insulated solely at the seals.

(f) Grids.

The main constructional problem in grid-building is differential expansion. Owing to differences both in the thermal capacity of different parts, and in their rates of heating by radiation and bombardment, this sets up strains leading to progressive distortion, unless the structure is so designed as to avoid such strains. For this reason, diagonally-braced grids were early given up and an adequate, though reduced rigidity was provided by thickening the longitudinal members.

If the μ of the valve is to be low, the grid consists simply of parallel rods; for higher values of μ a spiral of suitable pitch and thickness is added, secured by lacing spirals or, more recently, by welding. Grids in high-power valves are at present made wholly of molybdenum. The possibility of substituting tungsten for the purpose of reducing primary thermionic emission from portions overheated by radiation or bombardment has so far been held in reserve.

(g) Grid seals.

In the largest short-wave valves, *e.g.*, C.A.T.17, the grid seals have to have a large high-frequency current rating of 100 amperes or so in normal operation, and also a considerable margin to cover mistuning of the load and local concentration of high-frequency current. The construction of the seal has therefore to be so substantial that it may as well be used for insulation and support; in these types it therefore consists of a metal ring separating two parts of the bulb with a glass-to-metal seal on either side. These are the large $5\frac{1}{4}$-in. copper-to-glass seals already mentioned; copper-plated nickel-iron is also used.

When separate seals are used, the difficulty of so disposing the external conductors as to ensure equal distribution of high-frequency current restricts to two the number of seals which can usefully be considered. Given equal distribution, the inductance of the grid leads is of course halved. These separate seals are made like miniature anode seals, and direct copper-to-glass joints are now usually used, since their special troubles are least at the sizes required, whereas nickel-iron seals have to be copper-plated, and can be troublesome if too small.

Even in long-wave valves, grid seals of good high-frequency current rating have to be provided as a safeguard against emergencies arising from parasitic short-wave currents.

For the highest-power valves of the multiple-electrode class, such as pentodes, it has been found possible to mount a ring-cluster of separate seals in the foot-tube. A pair of seals at opposite ends of a diameter is provided for each internal electrode, so as to halve the inductance, which is further reduced by keeping all seals short. For the assembly of these clusters special glass-blowing appliances and technique have been developed.

Another possible form of grid seal, not yet extended to the largest valves, is the multiple-wire seal used in some of the smaller short-wave and ultra-short-wave types. This consists of as many wires as may be desired set in a ring, and passing either through the main glass-to-glass seal between bulb and foot-tube, or through a circular "pinch" on the foot-tube itself.

This sort of seal has been found to give a very good combination of high current-rating, and low grid-lead inductance, in consequence of which the types in which it is used have given lower wavelength limits, and better performance in that neighbourhood than were anticipated.

(h) Cathode seals and mountings.

The cathode seals in large valves have nowadays to carry heating currents of up to 700 amperes in operation, and considerably more during exhaust. In addition, the elimination of all internal insulators between the cathode and other electrodes requires that these seals should be strong enough to carry the whole weight of the cathode system, that is up to $1\frac{1}{4}$ lb., with the centre of gravity 24in. from the seal. A satisfactory solution of this double problem has been found in the use of a seal which is a miniature

replica of the well-tried anode-to-bulb seal. The smallest of these used is ½in. in diameter for 250 amperes. There has been no difficulty with progressive increase in size; the largest so far have a diameter of 1¼in. for 1,000 amperes or more.

For sealing to the two tubular extensions provided on the main foot-tube, the two seals are mounted on a common jig of nickel-iron, which has a spring grip to prevent temporary strain in the seal when the glass is setting. The stout copper extensions of the seals on the vacuum side have accurately-machined faces, to which the internal leads supporting the cathode system can be bolted in good alignment without further adjustment. It should be mentioned here that electrical contact between clamped metal surfaces is much better in vacuum than in air. In general it can be said that these seals behave as well as they do, because the design implies a fair division of responsibility between the mechanic and the glass-blower.

A further important but not so obvious function of the cathode seals and external leads is to remove the heat conducted back from the incandescent cathode, and also that generated by ohmic heating of the internal leads, which are designed as a compromise between these two effects. The total power to be dissipated amounts to 150 watts in each 700-ampere seal. There are two alternative methods in use, the first used was liquid cooling of the hollow external leads down to the point where they are screwed into the seal. The screw, incidentally, is greased to preserve the contact. The leads have to be provided with flexible centre sections of corrugated metal tubing in order to reduce strains on the seal, and in some of the earlier large valves water-leakage troubles have developed, usually after some 5,000 to 9,000 hours, through corrosion, possibly electrolytic, of these flexible "bellows" With the silver bellows more recently used this is unlikely. The other alternative, which is in several ways more convenient, particularly when the cathode is not at earth potential, is to substitute cooling by forced air-blast. With leads having fins machined on their inner ends, and air supply at 4in. level of water pressure, this method seems quite satisfactory.

(j) Cathodes.

We now come to the innermost component of the valves, the cathode system. The final form of this, simple though it is, is yet the product of a long evolution, in course of which the essential principles were successively appreciated.

To obtain an emission current of 165 amperes, which is the largest so far demanded, with a working life of the order of 10,000 hours, a total area of some 50 sq. in. (300 cm^2) of incandescent tungsten has to be provided. This takes the form of an assemblage of filaments of diameter 1·15 mm., requiring some 22 kW to heat them, and all mounted with a constant separation of 9 mm. from the adjacent wires of the grid.

The principal mechanical factors governing the design of these multiple-cathode systems are the unavoidable facts that in coming up to incandescence the longitudinal expansion of the filaments themselves is 1·2 per cent, *i.e.*, 4 mm. on a length of 350 mm., and that the lateral magnetic forces between the individual currents of 60 amperes or so tending to distort the system are by no means negligible, and are considerably greater than the electrostatic forces acting on the system when the emission is cut off or otherwise not space-charge limited. For dealing with the expansion, sliding guides are best avoided, especially if the sliding surfaces are at anything near red heat, because of the strong tendency of metallic surfaces to weld together under such conditions. If one of the surfaces is vitreous or ceramic, this tendency is probably less, but as we have seen, internal insulating bodies are avoided for other reasons. Further, friction between surfaces in vacuum is greatly increased, probably by the removal of gas films.

For these reasons less and less use has been made of such guides in the progressive evolution of cathode systems, until they have finally been eliminated altogether, leaving a free-hanging system supported only on its seals. That a good standard of reliability is achieved by the use of such systems has now been proved in service by several years' operation of valves of the largest size, and by the similar good behaviour of their immediate predecessors.

Their immediately obvious disadvantages of relative lack of rigidity and of apparent relative fragility were of course borne in mind from the first, but the event has shown that these were by no means so serious as might have been feared.

The resultant magnetic force between the current in one limb of the system and those in its fellow limbs depends on the method of connection of the limbs. This may be exemplified by a brief description of various types of cathode system which have been used. Currents and voltages will be quoted in round figures. In the earlier types up to C.A.T.5 there were two 10-volt loops carrying 50 or 75 amperes in series. This necessitated a silica spacing insulator, usually sliding on a central support, but in C.A.T.5 hanging freely from the two stout 1·3 mm. filament loops. In these systems the resultant magnetic forces are radial, and so small that the weight of the filament and insulator and the viscosity of the tungsten suffice to preserve the shape.

For smaller currents in the limbs, *e.g.*, C.A.M.2 with 12½ amperes, C.A.M.3, C.A.M.4 and C.A.T.6 with 35 amperes, and for higher wattage C.A.T.9 with 50 amperes, the series connection would give voltages about twice the preferred value of 20 volts,

so the two loops had to be connected in parallel. In C.A.M.2 the currents were so small and the limbs so short that the magnetic forces were still negligible, but in the others special steps proved to be necessary.

In such systems the resultant force is larger, and is more effective since the loops are twice as long. It acts slightly outwards of the circumferential direction, and any distortion tends to increase the force, not decrease it as in the series case. To counteract it, each limb is given an appreciable preliminary distortion in two ways. The ends of each loop are set 6 mm. apart, which is closer than the 10 mm. separation of the central parts, and again both loops are bent in their own planes so that the ends are 14 mm. apart. The resulting shape of each loop is that of the gunwale of a boat, with a rise to bow and stern. The tension required to keep the loops so shaped in equilibrium is applied partly by the weight of the sliding central support, and partly by a spring acting on its outer end and pushing it downwards. The resulting system is stable throughout life, though, if the spring is defective, distortion becomes apparent after a few hundred hours.

It will be noted that in the parallel connection the tips of the loops are at the same potential and require no spacing insulator. Now the advantages of the series connection can be recovered if good electrical connection is made between the tips of the loops, and the supply leads are forked and crossed so that similar polarities appear at opposite ends of a diameter. The currents then run opposite ways in alternate limbs, as in the series case, and also—which is a great advantage—points at the same level on alternate limbs are at the same potential, and can be connected by finer wires, the tensions developed in which can counteract the resultant magnetic forces.

This principle of construction can be extended to include any even number of limbs, and it is adopted in all the larger types of valve. Thus C.A.T.10 has 6 limbs with triangular bracing wires, C.A.T.12 the same number on a wider base, C.A.M.6 8 limbs with square bracers, C.A.M.5 12 with interlaced triangular bracers, C.A.T.14 16, and C.A.T.19 24, the two last-mentioned with interlaced square bracers. The thick molybdenum leads are blackened to assist dissipation of heat by radiation, and are sawn into the required number of segments, and these are then bent to a jig so that they interlace accurately when assembled. The filament ends are arc-welded directly into holes or slots in the ends of the leads. This gives a slightly brittle joint, but, if required as in C.A.M.2, this brittleness can be dealt with by providing a clamp between the arcing point and the body of the filament. After arcing at the support end, the limbs of the multiple systems are adjusted to come together symmetrically at the far end without strain, and are then arced either all together in one operation, or in succession to a flexible ring of sheet molybdenum. The cross-bracing wires are then fitted in small V bends in the limbs placed to receive them. The spacing of the bracers is determined by the weight of the filament system below each bracing level.

The resulting system should be free from strain but any residual strains are removed by raising to incandescence in a neutral atmosphere.

Appreciable distortion in after life is very rare. The stability of the system against electrostatic forces was established by means of a model in which weighted chains were substituted for the filaments.[2]

The presence of the cross-bracers also prevents an effect which had been troublesome in the smaller systems. This is the curious fact that the natural frequency of transverse elastic vibration of a tungsten filament, whatever its diameter, having the length required for a 19-volt working potential-drop between rigidly fixed points, is always very close indeed to the 100-cycle frequency of the magnetic forces due to a 50-cycle a.c. heating current. This natural frequency varies over a range of 20 per cent between cold and working temperatures, and therefore a resonance can easily occur during heating up, and, if the voltage applied results in currents in excess of the normal passing through the cold and brittle filament, the consequent vibrations in the plane of the loop can be notably destructive, breaking the loop at the tip. In the design of C.A.T.9, the natural frequency has had to be lowered to a safe value by making the ends of the supports themselves flexible in the plane of the vibration.

As in the case of the cathode seals there is no obvious difficulty in constructing still larger cathode systems on the free-hanging principle. Indeed, the mechanical stability is unaffected as the diameter increases, so that once the narrowest practical system, seen in C.A.T.10, was found satisfactory, the way was seen to be clear for larger systems.

Cathodes are still generally heated by direct current, but if more than two seals are provided, which on the present systems can readily be done, polyphase alternating current can be used, and in particular with four seals the hum-reducing connection using two phases in quadrature or otherwise.

(k) Cooling of anode.

The rate of transfer of heat from the anode surface to the cooling fluid is so high, of the order of 1 kW per sq. in., that the actual mechanism of the process may be peculiar to valves. This has been investigated.[2] Space does not permit description of the work, but the results may be briefly summarized. The surface temperature of the anode is found by an embedded thermocouple to reach the boiling point of the liquid at comparatively low power dissipations. Various oils were studied, as well as water. Thereafter it can rise very consider-

ably, as much as 40 degrees C. in some cases, even at our usual somewhat conservative rated dissipations. Heat transfer at these high rates is evidently facilitated through the formation of small bubbles of vapour, or of dissolved air if present, which break up the stagnant film of liquid in contact with the anode. Further, there must be some transfer in the form of latent heat of condensation of the vapour.

These processes evidently provide a very effective convection of heat, quite apart from the general motion of the liquid over the surface. It is thus doubtful if spontaneous turbulent motion is really necessary, and it may be remarked that, according to Osborne Reynolds's laws, mere constriction of the space between anode and jacket does not increase the probability of turbulence for a given volume of fluid passing. It should reduce the thickness of the effectively stagnant film, and seems to do so at the lower dissipations, but at the higher it also definitely retards the break-up of the film by small bubbles. At the higher dissipations certainly the results show that constriction can be a disadvantage. This is further illustrated in the case of low μ modulator valves, in which the bombardment is focused on the anode in streaks, and, in consequence, the cooling conditions become more complicated. Here constriction of the jacket lowers the temperature only a little, and is accompanied by irregular flow, setting up severe vibration. Probably the flow is intermittently diverted from the hot streaks by formation of large bubbles trapped by the constriction. The focusing effect has other curious results, which show that it is the overriding factor in such valves. Thus, if the anode voltage be fixed and the kilowatts dissipated be reduced by increasing the grid bias, the streak temperature is practically unaffected over a range of some 6 : 1 in dissipation, sharper focusing compensating for reduction in dissipation. Again, increase in anode diameter can increase the streak temperature owing to sharper focusing; it does so in C.A.M.4 as compared with C.A.M.3. Between the streaks the temperature does not rise above the boiling point. These valves are very sensitive to the cleanliness of the anode surface. If hard water is used a temperature of 250° C. can be attained.

More recent work appears to show that a forced air blast can be substituted for liquid cooling in any type of valve operating, as is usually the case, somewhat below the rated dissipation for water-cooling. For this, the surface for heat transfer is very greatly increased by soldering to the anode either blocks of copper perforated by a great number of holes, or a very closely spaced set of radial fins. By this means the anode temperature can be kept down to 140°C., which, as we have seen, is a quite usual value for water-cooling.

EVACUATION—THE EQUILIBRIUM STATE.

(a) General.

The general principle followed in all exhaust schedules is to subject each part of the valve for a sufficient time while it is on the pump to conditions more severe than it will meet with in operation. Thus the filament is overburnt, at the cost it may be of a few hundred hours of life, the grid is heated by bombardment to just short of the point where appreciable evaporation from the hotter parts would occur, and the anode is overheated with or without water-cooling—and we have already seen that even with water-cooling there can be considerable overheating given sufficient overload. The anode is not necessarily bombarded at all.

In the types which have bright emitting filaments no getter is used; as we shall shortly show, it is not needed. Independent evidence that this procedure has a sound basis is provided by the observed fact that gas evolution from heated metals and also from glasses is enormously reduced by a relatively small lowering of the temperature.

In addition to higher dissipations, higher voltages are applied in order to accelerate the fatigue of any tendency to flash-arc breakdown in the insulating properties of the vacuum, there being, as we have seen, no other insulation which is under any serious stress.

The schedules are judged by their results, and, where numbers permit, statistically, and in the light of reports of performance in operation.

This kind of procedure is necessary if the reliability of the product is not to be jeopardized by changing the schedules in ways which may prove to be ill-advised. Clearly, however, the further it is removed from the plane of trial and error by increasing insight into what is actually happening in the valve in manufacture and in operation, the more quickly will improvements be made and faults eliminated.

The true nature of the accepted gas test and the general behaviour of residual gas in valves with substantially cold anodes thus came in for investigation, and in both cases the results were somewhat surprising. Naturally, what was happening to the gas was much better understood when the test had been studied, so we shall take the work on the test first.

(b) The gas test and its meaning.

The discriminating test is the now well-known backlash or gas test, in which the reverse grid current or "backlash" is measured under standard conditions of anode voltage and dissipation, the grid being necessarily negative. The backlash ratio is defined as the ratio of reverse grid current to anode current, and is usually expressed as microamperes per ampere. At a relatively late stage in the develop-

ment of standard methods of exhaust it became clear that for hard valves the interpretation of the backlash test was more complex than was at first supposed. The simple ionization gauge law does not apply, *i.e.*, the backlash ratio is not directly proportional to the equilibrium pressure. The factors which led to this conclusion are stated and discussed later, but to simplify the discussion a brief summary of the explanation is given at this stage.

In order to account for the observed behaviour of the backlash ratio r, it is necessary to assume that the reverse grid current contains two components: (1) the positive ion component r_p obeying the ionization gauge law which is of major importance for soft valves, and (2) a component r_0 of unknown origin which is of major importance for hard valves, where $r = r_p + r_0$. The experimental investigation was concerned, therefore, with the nature of r_0. Analysis of various test results had shown that r_0 continues to exist at substantially zero pressure; the residual grid current cannot, therefore, be a positive ion current, and must be an emission of electrons from the grid.

Consideration of the mechanism of this emission proved it to be photo-electric in origin, and caused by exposure of the grid to soft X-rays produced at the anode surface.

The principal features of the test results which the investigation had to explain, were as follows:—

First statistically, *i.e.*, from large numbers of valves:—

(1) In a series of valves of identical construction the backlash ratio is never observed to fall below a certain limiting value. This needs little explanation on the photo-electric theory, because if gas were entirely absent, the backlash ratio would reach the limiting value r_0.

(2) Of freshly pumped valves, the majority show backlash ratios near to the limit, and few stray upwards to as much as 50 per cent more. This spread is unlikely to be due entirely to variations in gas pressure, owing to the enormous clean-up capability of water-cooled valves (described later). It is due only partly to slight changes in gas pressure, but partly to variations in the photo-electric component caused by adsorbed gas or traces of other impurities on the electrode surfaces.

(3) For valves differing in little besides the material of the grid, the limit is distinctly lower for molybdenum grids than for tungsten grids. For any type of valve r_0 for molybdenum is about 70 per cent of r_0 for tungsten. No satisfactory explanation could be found for this observation before the photo-electric theory was advanced, unless it was assumed that the residual gas pressure was actually lower in molybdenum grid valves, owing to gettering by the more volatile molybdenum. Although the residual pressure in a well-pumped valve is close to the limit of measurement, such a difference, if it exists, should have been detected by ionization gauge measurements. However, the photo-electric theory provided the explanation, as it was found that under the action of soft X-rays from copper the photo-electric emission from molybdenum is about 70 per cent of that from tungsten.

(4) For valves differing only in the diameter of the anode, the limit is lower the greater the anode diameter.

It was this last observation, more than any other, which led to a detailed investigation of the real meaning of the backlash test. For, if the reverse current is due entirely to gas, one would expect the backlash ratio to be greater in large anode valves because the electron paths are longer, and therefore more positive ions are produced. It was thought at first that for some reason the equilibrium pressure might be lower in large anode valves; and to decide the point a double valve having identical, but separate, grid-filament systems, and anodes of different diameter, was assembled inside a common envelope. This valve was known as the "Siamese Twin," and took the form of two valves with their anodes joined end to end, so that the communicating hole had the diameter of the smaller anode. There could thus be no question of a difference in pressure. Now when this double valve was hard, it was found that the large anode valve showed the lower backlash ratio. If the gas pressure was increased, however, the behaviour was as expected, and the backlash ratio increased more rapidly in the large anode valve, which eventually gave the higher backlash ratio. The pressure at which the backlash ratios were equal was about 2×10^{-5} mm. of mercury for anode diameters of $1\frac{3}{4}$in. and 3in. This result demonstrates clearly that for well-pumped valves gas ionization contributes little towards the reverse grid current.

Now, on the photo-electric theory the explanation is quite simple. As the anode is moved further away from the grid, the X-ray intensity at the grid surface and, consequently, the photo-electric emission fall off—inversely as the anode diameter for a circular cylindrical system. This is in good agreement with observations on different types of valve where anode diameter is the major variable.

Secondly, in addition to the above information from finished valves, we have, as a result of experiment:—

(*a*) For valves near the limit, the reverse grid current is proportional to the anode current at constant anode voltage, *i.e.*, the backlash ratio shows little or no variation with the anode dissipation. This, of course, is true whether the grid current consists entirely of positive ions or of photo-electrons. It is only in very soft valves that the backlash ratio is appreciably affected by anode dissipation.

(*b*) For valves which are not fully bombarded, the backlash ratio is higher than for fully-pumped valves, although the residual gas pressure may be the same for both. A separate X-ray photo-electric experiment showed that for constant conditions of

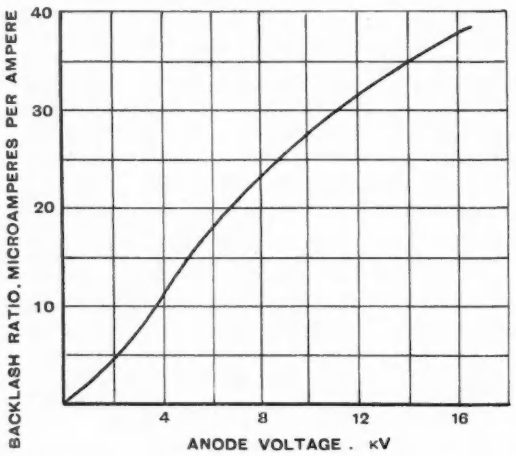

Fig. 2.—Variation of backlash ratio with anode voltage for a hard valve, type C.A.M.2 (molybdenum grid).

X-ray generation, the number of photo-electrons liberated depended on the state of the molybdenum and tungsten surfaces. For surfaces which are treated in the same manner as grids for cooled-anode valves, adsorbed gas produces an increase in the photo-electric emission.

(*c*) For valves near the limit, the backlash ratio varies in a characteristic manner with the anode voltage (see fig. 2).* This observation was at first as mysterious as the variation of backlash ratio with anode diameter. According to all experiments on ionization by collision, an increase of anode voltage in the range of voltages used should have resulted in the production of rather fewer positive ions, and consequently, in a lower backlash ratio. However, the photo-electric theory disposed of the mystery, for reference to fig. 4 will show that the curve relating photo-electric emission from molybdenum with X-ray exciting voltage is very similar to the backlash ratio-anode voltage curve for a molybdenum grid valve. There can be little doubt, therefore, that the increase of backlash ratio as the anode voltage is raised is caused by an increase in the photo-electric component of reverse grid current due to the increased intensity of the X-radiation.

It will be seen that the photo-electric explanation adequately fits all the previously anomalous observations. There has, of course, been no direct confirmation in an actual valve; such a test would necessitate screening the grid from X-rays, which is quite impracticable. However, the evidence in favour of this explanation is so complete that no doubt exists of its accuracy.

Other possible explanations were considered before the photo-electric theory was finally accepted. Various possible causes of grid current exist, including such factors as leakage across insulators, positive ion emission from the filament, and primary electron emission from the grid, but in water cooled valves these factors, if present at all, are of negligible magnitude. Besides, the observed dependence of the residual reverse grid current on anode diameter and anode voltage narrowed the field of the investigation, and reduced the possible explanations to two :—

(1) the photo-electric explanation already discussed, and (2) an emission of electrons from the grid due to bombardment by high-velocity positive ions produced on the anode surface. This second hypothesis was also investigated experimentally in a valve having an extra grid placed close to the anode, by means of which the field at the anode surface could be reversed, thus preventing the escape of any

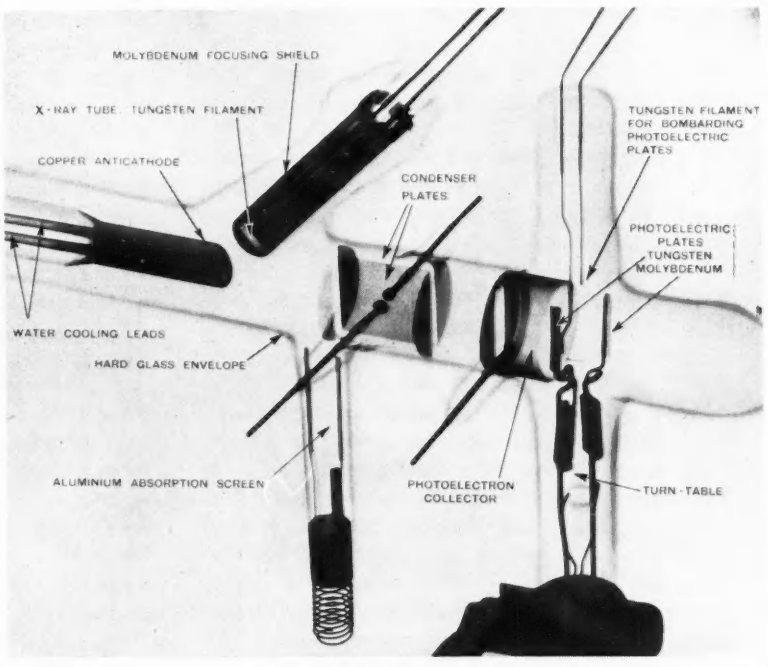

Fig. 3.—Radiograph of the apparatus used to study the photo-electric emission of electrons from tungsten and molybdenum under the action of X-rays from copper.

* The pursuit of this investigation was encouraged by information from Mr C.R. Burch, that curves similar to that of Fig. 2 were normally obtained from continuously-pumped valves of the Metropolitan-Vickers demountable type.

positive ions formed there. The result of this experiment was entirely negative.

Photo-electric emission of electrons from tungsten and molybdenum under the action of X-rays from copper. It is impossible, in an actual valve, to separate the photo-electric component of grid current from the gas component. The apparatus shown pictorially in fig. 3 was therefore built to study the emission of electrons from grid materials, *i.e.*, tungsten and molybdenum, under the action of soft X-rays from copper.[4]

The radiograph is self-explanatory, and it will be sufficient to mention that the X-ray tube filament corresponds to the valve filament, the copper anti-cathode to the valve anode, and the photo-electric plates to the grid, either tungsten or molybdenum. Hence the X-ray tube voltage is analogous to anode voltage, the X-ray tube current to anode current, and the photo-electric emission to grid current. The ratio of photo-electric emission to X-ray tube current is therefore analogous to the residual backlash ratio.

Fig. 4 shows the result obtained after thorough degassing of the photo-electric plates. The increase of photo-electric emission as the X-ray exciting voltage is increased is due to the increased intensity of the soft radiation, and not to the appearance of progressively harder rays. This was proved by tests with an aluminium absorption screen. Tungsten shows a greater photo-electric emission than molybdenum, the ratio being approximately that previously observed in valves.

It will be seen from fig. 4 that the qualitative agreement between the experimental results for molybdenum and a molybdenum grid valve is good, and the agreement for tungsten is equally close. Quantitatively, the results obtained from the experiment just described may be used to calculate, by considering the relevant solid angles, the value of r_0 for a valve of any given geometry. Firstly, for a modulator valve having a parallel wire or "squirrel cage" molybdenum grid the experimental results predict a value of r_0 of 14×10^{-6} at 13 kV, whereas the observed value is 29×10^{-6}. Secondly, for a high μ tungsten-grid valve, the predicted value of r_0 is 28×10^{-6}, and the observed value is $45 \times 10.^{-6}$ In both cases the calculated value is low, which may be due to an enhanced photo-electric emission in the valve caused by secondary X-rays.

The effect of adsorbed gas or other contamination on the molybdenum and tungsten plates was examined in the experimental apparatus. It was found that, after heat treatment corresponding to normal pumping of a valve, gas contamination increased the photo-electric emission, although other forms of contamination could reduce it. Hence, small changes of backlash ratio are not necessarily due to changes of equilibrium pressure, but may be due to traces of adsorbed gas or other contaminant on the electrode surfaces.

(c) Clean up of free gas.

A fully-exhausted water-cooled valve, with its large and very clean metal surfaces, forms a most effective pump and is capable of cleaning up surprisingly large quantities of free gas. Bearing in mind this large, but limited, clean-up capability, it becomes clear that one of the objects to be kept in view in developing exhaust schedules is the production of a valve capable of cleaning up, if required, the largest possible amount of gas liberated in operation. The clean-up capability may be measured in terms of the volume of gas cleaned up before the equilibrium pressure starts to rise.

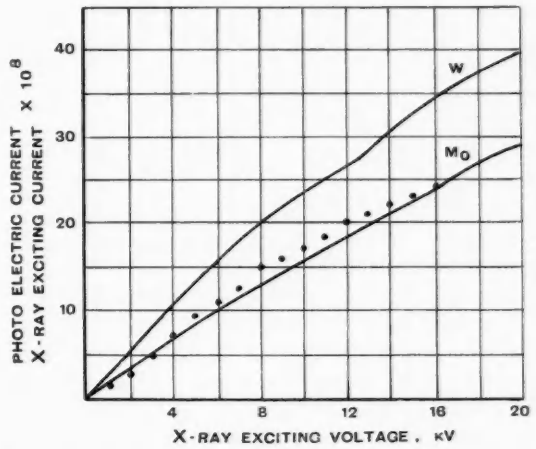

Fig. 4.—Photo-electric emission from clean tungsten and molybdenum under the action of soft X-rays from copper.

The points ⊙ are backlash ratio points, taken from fig. 2 for a hard molybdenum grid valve (ordinates adjusted to fit at 16 kV).

The volume of gas required to exhaust the clean-up capability completely has not been determined, but for a valve having a volume of about 1 litre several cubic centimetres of air at normal temperature and pressure have been cleaned up under experimental conditions without by any means exhausting the clean-up capability. This corresponds to a reduction in pressure from 1 mm. of mercury to less than 10^{-6} mm. of mercury. Of course this degree of clean-up was not carried out in one stage. The experimental procedure, having first of all exhausted the valve in the normal manner, was to admit the gas in small doses, each dose being cleaned up before the next was admitted. Clean-up was produced by operating the valve under backlash test conditions which are known to be favourable.

This explains the recovery of valves accidently softened, for example through failure of the water supply. Cases have been recorded where such an accident caused the pressure to increase to the point where a glow discharge occurred, but operation of

the valve under backlash test conditions with gradually increasing dissipation soon restored the vacuum to something approaching its original value.

Certain operating conditions are conducive to clean-up, notably those in which anode current flows when the grid is negative, at any rate for part of the operating cycle, *e.g.*, normal "class B" or "class C" operation. Conversely, conditions in an absorber biased beyond cut-off when inactive and passing anode current only when the anode potential is low and the grid is at a high positive potential, are not favourable to clean-up.

In practice this large clean-up capability renders the use of getters unnecessary. This is illustrated in fig. 5, where the variation of backlash ratio during life is shown for valves which are now known to have had a continuous source of gas, namely a small piece of very slightly overheated mica. Curve A is for a valve with a poor clean-up capability, *i.e.*, it is saturated when only a little gas has been absorbed, and the backlash ratio starts to rise early in life. The valve, however, would have been satisfactory had there been no source of gas. Curve B represents a valve having a greater clean-up capability, and the same source of gas as A. Here the backlash ratio is unaffected for 1,000 hours, but once the clean-up capability has been exhausted the pressure rises. Curve C is typical of present-day performance, where the clean-up capability is large and there is no serious continuous source of gas.

The smooth curve of fig. 6 shows curve B of fig. 5 replotted after subtracting the photo-electric component from the total backlash ratio, and it will be seen that the relation between time and the logarithm of pressure is linear over a considerable range. The straight portion is not always so long; but, nevertheless, it encouraged a search for a theoretical exponential relationship between pressure and time, but this could not be found on the assumption of a constant source of gas and clean-up by simple adsorption. However, this mechanism does account at least qualitatively for the general shape of the observed curve.

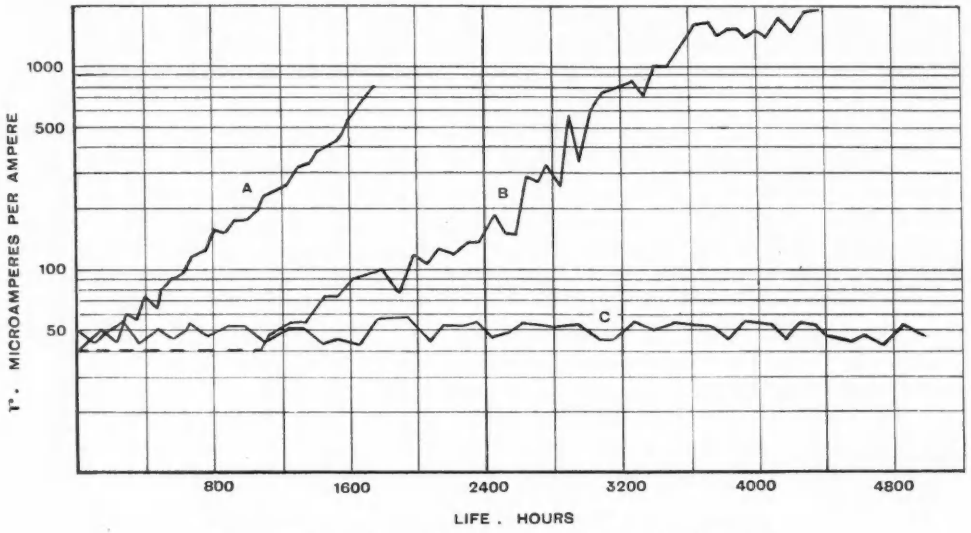

Fig. 5.—Variation of backlash ratio "r" for valves which soften during life.

Curve A. Valve with continuous source of gas and poor clean-up capability.
Curve B. Valve with continuous source of gas and greater clean-up capability.
Curve C. Valve with no serious source of gas and large clean-up capability.
Valve Type C.A.T.6.

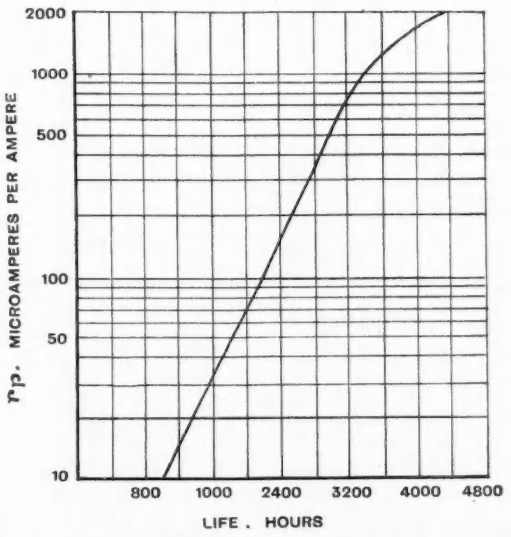

Fig. 6.—Variation of r_p, the gas component of backlash ratio, for a valve (type C.A.T.6) which softens during life. Curve B of fig. 5 replotted after subtracting r_0, the photo-electric component.

CONTROL OF SATURATED EMISSION.

(a) General.

Although it is possible to obtain uniformity of performance between valves of a given type without much attention to the design and performance of their cathodes by providing a great reserve of emission so that no valve approaches thermionic saturation, such a procedure is expensive in respect of valve life, and particularly so in the case of bright-emitting tungsten filaments in which evaporation at emitting temperatures is appreciable. Means are therefore necessary for ensuring that valves of a given filament

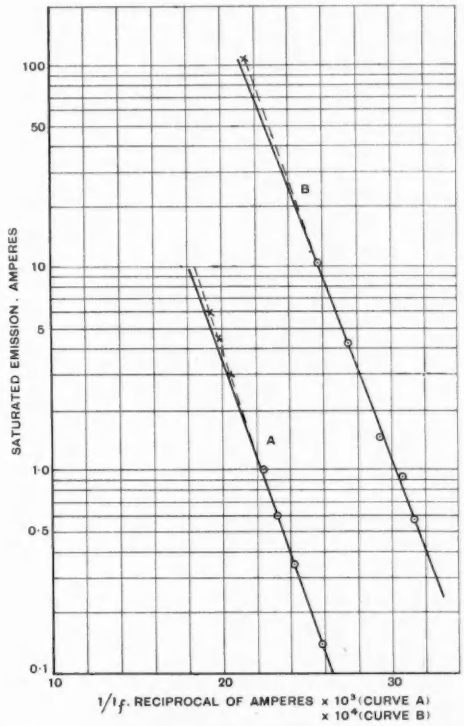

Fig. 7(a).—Extrapolation from reduced to full emission, simple method ; log. of emission plotted against reciprocal of filament current.

Points ⊙. Normal test observations.
Points × (curve A). Additional observations for checking extrapolation.
Point × (curve B). Extrapolated point, using method of fig. 7(*b*).
Curve A. Simple filament, valve type C.A.R.2.
Curve B. Multiple filament, valve type C.A.T.14.

design, selected by the methods described by le Rossignol and Hall,[2] are operated as nearly as possible at the same emission. The regularity of performance attainable by taking full advantage of these means is illustrated in Part II. (fig. 19).

When emission data for individual valves are available, the rated values of filament voltage and current become quantities of secondary importance, subject to minor adjustments which are made when each valve is installed. The range of adjustment needed in practice has become less and less as the possession of emission data has reacted on the technique of filament manufacture.

It is impracticable in a routine test to take the full emission from the cathode continuously because of damage to the valve through overloading, except in the case of some low-impedance rectifiers, and also because the test may be misleading through overheating of the filament ends by the superposed space current, and so forth.

Hence, either the electrode voltages must be applied intermittently, or a reduced emission must be measured. The intermittent-voltage method has long been used for glass valves, the peaks of space-current being read on a peak-voltmeter connected across a resistor.

(b) The reduced-emission test.

For high-power valves in which the full emission may be some tens of amperes the reduced emission method is preferred. The principle of this is to record readings of filament voltage and saturated emission, the values of emission increasing in roughly constant proportion over a total range of about 20 : 1, and then extrapolate to obtain the filament voltage required for the full rated emission. Since a graphical

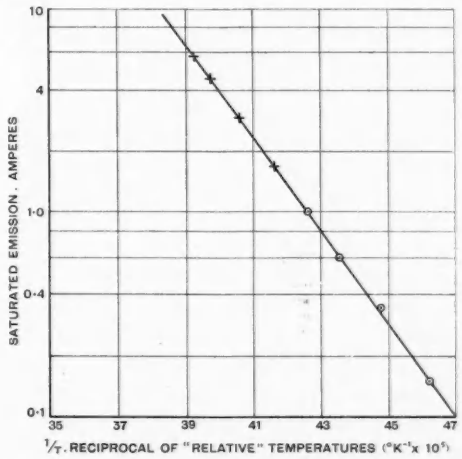

Fig. 7(b).—Extrapolation from reduced to full emission, standard method ; log. of emission plotted against reciprocal of "relative" temperatures.

Points ⊙. Normal test observations.
Points ×. Additional observations for checking extrapolation.
Valve type C.A.R.2.

method of extrapolation is the most convenient, some way of plotting in which the observed points lie on a straight line which can be produced upwards has to be established.

For taking the readings the filament is heated with alternating current, since with direct current local overheating of the negative end by the superposed space-current may not be negligible. It can readily be shown that with a heating current H leaving the positive end of the filament and space-current of wave-form such that it has a mean value S_{mean} and an r.m.s. value $S_{r.m.s.}$ the equivalent heating current for producing the same local temperature in

a non-emitting filament is

$$\sqrt{(H^2 + S^2_{r.m.s.})}$$

for alternating current, and

$$\sqrt{(H^2 + 2S_{mean}H + S^2_{r.m.s.})}$$

for direct current. The effect on the local emission can be estimated from the local overheating so defined.

If a more general treatment of the distribution of overheating is required, the same formulae will be found to apply to each elementary length of filament, provided that only the space-current emitted from the part on the positive side of the element is used; its value has to be obtained by integration, starting from the positive end.

Since even bright-emitting tungsten is susceptible to emission-poisoning at reduced temperatures, the filament is flashed at the full voltage before taking readings, and then the lower emissions are taken first. Further, the positive voltage is applied to all the other electrodes together. This is again to reduce the chance of poisoning, since in a water-cooled triode, for instance, a combination of high anode voltage and low grid voltage can produce poisoning when a lower voltage applied to anode and grid does not. The control grid then takes up to about one-quarter of the total space-current, and if for the higher emissions the grid watts for full saturation are excessive, a lower positive voltage is used, and a small extrapolation to full saturation is made as described later in this Section.

(c) Extrapolation to full emission.

Figs. 7(*a*) and 7(*b*) show two methods for the final extrapolation to full rated emission. Clearly the simple plot of log I_e against $1/I_f$ will only do for small extrapolations, although it is by far the best of such simple methods; whereas the method illustrated in fig. 7(*b*) is much better, and this is, in fact, used for extrapolations up to as much as about 10 times the highest observed value.

The result of the extrapolation is to provide for each valve filament a "marked voltage" at which it gives a stated emission current which is 90 per cent of the value obtained from the plot, and is described as "90 per cent saturated." This 90 per cent figure is adopted as being more useful to users, since the slow final approach to full saturation makes it unlikely that the 100 per cent value will ever be used in practice.

The plot is not necessarily made for every individual valve. In many types it is found sufficient to determine from a number of plots a standard extrapolation factor. For example in one well-known type, C.A.T.14, the "marked voltage" for 100 amperes 90 per cent saturated (111 amperes full saturation) is found to be 1·31 times the voltage observed for 10 amperes fully saturated, and the factor for that type is 1·31, which can be applied to a single test reading at 10 amperes emission. The variation of the factor for individual valves seldom exceeds $\pm$ 0·7 per cent.

The method of plotting in fig. 7(*b*) is based on the Richardson equation $I_e \propto T^2 e^{-b/T}$, but the T^2 term is negligible, and the T of the plot need not be a true temperature but can be anything whose reciprocal is a linear function of the true reciprocal temperature. The "relative" temperatures used for the plot are obtained by the following rapid approximation. The reading of filament current A is used and the corresponding relative temperature T_1 for a filament of length l_f and diameter d_f is found from Langmuir and Jones's[5] tables using the relation:

$$A = A' d_f^{\frac{3}{2}}; \quad A' = \sqrt{(W'/R')}$$

where A′, W', and R', are the heating current, power dissipation, and resistance of 1 cm. length in a filament of 1 cm. diameter at temperature T_1.

This relative temperature T_1, then corresponds to current A, voltage V_1, and emission I_{e1}. Using Langmuir's second relation:

$$V = V' \frac{l_f}{d_f^{\frac{1}{2}}}, \text{ where } V' = \sqrt{(W'R')}$$

the other temperatures T_2, T_3, etc., corresponding to the other voltages V_2, V_3, etc., are found, and the plot is made.

The series of voltmeter readings V_1, V_2, etc., is preferred to a series of ammeter readings A_1, A_2, etc., because the combination of voltmeter and resistor is considered to be more permanently reliable than that of ammeter and current transformer, and because even a slight error in converting from amperes to volts after extrapolation might be serious.

Other similar methods have been examined, but the one here followed is found to be the most accurate. Since the voltage readings are actual terminal voltages, this process ignores corrections for graded cooling at the ends and supports of the filament, but these corrections are known to vary little over the range of temperature in question. This is one reason why the temperatures plotted are only "relative." Another and more fundamental reason is that the resistance property R' of the actual filament may not be the same as Langmuir's, nor the radiation property W' of the actual filament in its actual surroundings, which may vary in temperature and in reflecting power. Nevertheless, this will not matter so long as these properties preserve a due proportion over the range of temperature. There are two checks on the process available, one is to verify it directly with a plot of readings taken all the way to full emission without extrapolation, using a low impedance diode such as a standard water-cooled

rectifier. This has given a very satisfactory confirmation, as illustrated by the points X in fig. 7(*b*).

The other check is to calculate from the slope of the plot the value of the coefficient corresponding to the *b* of Richardson's equation, and it is found that when this is done the values of *b* obtained agree closely with the accepted value of *b* for pure tungsten.

(d) Emission statistics.

The results of the reduced emission test for the first 61 valves to which it was applied are shown in fig. 8, the position of each dot representing the amperes and volts required to produce the standard emission current, 1·0A 90 per cent saturated. The extreme range of variation is ±5 per cent in volts and amperes, *i.e.*, ±10 per cent in watts.

The marked elongation of the pattern indicates either that the observed variations had only one physical cause, or that if there were more than one cause then the several causes must be such as to produce closely similar effects. The axis of the elongation has been determined by the method of least squares; if a larger number of observations had been available, the direction of the axis might have been a little different, but the chances are 20 to 1 against it ever, for any batch of similar size, lying outside the broken lines, on either side of the axis shown.[6] Each of the other "axis lines" indicated on the diagram shows to a close approximation the direction which the elongation would have taken if only one physical quantity, that marked on the axis, had been subject to variation. Thus, to take the simplest case, variation in length will affect the voltage, but not the current, required to bring the filament to a given temperature. To reproduce the standard emission there would have to be a readjustment of the temperature to compensate for the change of area. Since, however, the emission varies very rapidly, this readjustment would be very small, so that the "length axis" will be a substantially horizontal line, as shown.

The direction of the actual elongation lies very close to the axis of thermal emissivity, that is, of the variation in watts required for filaments of the same dimensions and resistivity owing to variations in their thermal radiation to their surroundings. Under these conditions the resistance is constant, and the current and voltage will increase or decrease together and to the same extent, as the direction of this axis shows.

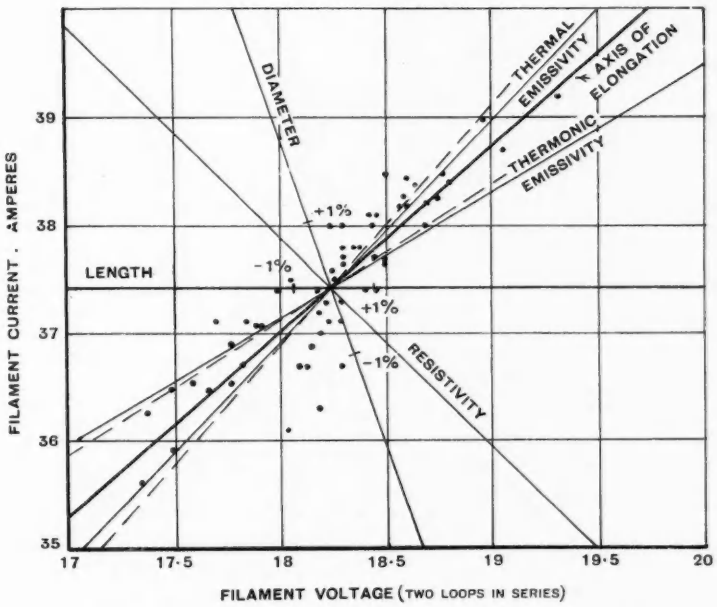

Fig. 8.—Reduced emission test, target diagram, showing axes of elongation expected from variation of each quantity (as marked) alone. Early valves (type V.T.26).

It is interesting to note what would be the effect on the diagram of variations in length and diameter, separately or together. These filaments were actually some 230 mm. long, so that variation in length exceeding 1 per cent must be regarded as very unlikely. The drawing of the wire is not, however, so easy to control, and variations of this order in diameter are much more probable.

Variations in length alone would thus produce only a very small elongation on the scale of the diagram; but variations in diameter would have a perceptible effect. Variations of both together would produce a small elongation in the direction of the diameter axis, but with some lateral spread. The

point of interest is that a marked elongation in the direction actually observed could not result from independent variations of length and diameter, though the lateral spread could very well do so.

For such an elongation to result from variations in dimensions there would have to be a definite connection between the two, in the sense that all thin filaments would have to be short and all thick filaments long, and to a most unlikely extent. Since the two dimensions are under completely separate control this must be considered impossible.

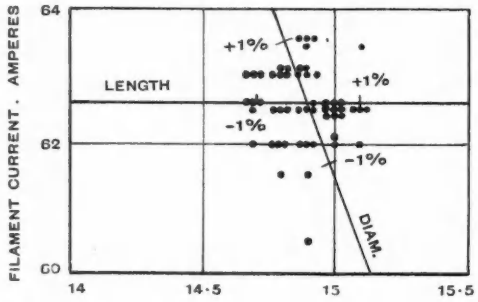

Fig. 9.—Reduced emission test, target diagram. Recent valves (type C.A.T.6).

The axes of thermal and thermionic emissivity are too close together for any definite distinction between these two causes to be made on the evidence shown in the diagram. All that could be said is that thermal emissivity is the more likely cause.

However, thermionic emissivity should be sensitive to heat treatment of any filament between repeated tests. No marked effects of that sort were observed, so that variations in thermal emissivity remained as the most likely cause of the observed elongation.

This conclusion indicated that the technique of wire drawing as affecting the final state of the surface of the filament required attention, and steps taken to ensure that filaments had a smooth bright surface resulted in a distinct and maintained improvement,[7] as exemplified in fig. 9, showing the results of reduced emission tests on representative later valves of similar filament construction. The larger valves with multiple-filament systems containing more filament limbs must be expected to give still more uniform results, since these give an average of the performance of the individual limbs.

The improvement between the valves of fig. 9 over those of fig. 8 illustrates the value of a suitably designed and easily performed test on an isolated property of the product, once the meaning of the test has been sufficiently analysed.

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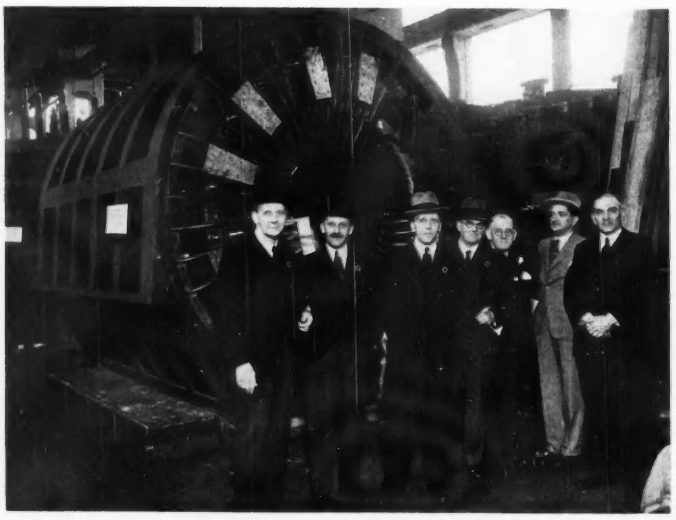
[*To be continued*]

I.E.E. Members at Witton Engineering Works.



A group taken during the visit of the Institution of Electrical Engineers (Summer Meeting, 1938) to Witton Engineering Works on Tuesday, 5th July. Left to right: Sir Archibald Page, Dr. A. H. Railing, Mr. Johnstone Wright, Mr. S. T. Allen, Dr. C. C. Garrard, Mr. A. M. Anderson and Mr. H. N. Sporborg.

A Review of the Report of the Ministry of Transport Departmental Committee on Street Lighting.

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IT is some indication of the public interest in street lighting that in June 1934, the Minister of Transport appointed a Departmental Committee "to examine and report what steps could be taken for securing more efficient and uniform lighting with particular reference to the convenience and safety of traffic and with due regard to the requirements of residential and shopping areas, and to make recommendations." In September 1935, an interim report was submitted, and in August 1937, a final report. Many important bodies gave evidence both written and oral, and experimental work was undertaken, principally by a technical panel, to assist in framing certain of the conclusions and recommendations.

There is always danger in a review of this kind of incorrect conclusions being drawn from extracts taken out of their context. It cannot therefore be urged too strongly that reference should be made to the original report for an authoritative statement on any point.

The aim of this review is to present an engineer's picture of the report after a year's experience of its use, and to draw attention to those items which appear to the writer to be its salient features.

In its technical provisions, the report is a courageous crystallization of the results of investigatory work carried out in recent years; and the fact that at the present time numerous installations are being erected in accordance with the recommendations is some indication that the report has achieved results which would have been long in coming if the findings of investigators had to be appreciated in the usual leisurely way.

The report gives, in the main, the conclusions reached by the Committee rather than the detailed reasons which lie behind their conclusions; but it is evident that in making their recommendations they have been guided by the results of recent work on street lighting and have recommended a design which is generally in accordance with good practice at the present time. The subject is advancing rapidly; it is only to be expected that in some details the report may soon become out of date, and experience may show some small modifications of detail to be desirable. In its broad lines, however, particularly in the matter of siting, there is little doubt that it has laid a foundation of good practice upon which the more detailed improvements of light distribution, improved lantern designs, and so on, which will certainly be developed, can be well built. Critics have attacked the report because on the one hand it is too detailed, and on the other hand because it is not detailed enough. Both are probably right, for while some parts of the problem can be specified in some detail, it would be folly to tie the designer's hands in other matters where there is obviously room for individual experience and where specification cannot be rigid. It is fortunate that the detailed parts of the report include precisely those matters of fundamental design which it is important to have standardised, such as the height of the sources and their position. If these are settled the designer of apparatus can proceed upon some definite foundation. Problems of light distribution, glare, etc., are much less defined at present and in any case much more difficult to define; and it is here that the report wisely gives the designer a much freer hand.

ADMINISTRATION OF STREET LIGHTING.

To the practical engineer the technical recommendations are of the greatest interest, but it should not be overlooked that the report contains in Section II, suggestions on the administration of street lighting which are of far-reaching importance. The recommendation is made that consideration should be given to confining the responsibility for the lighting of classified roads (and such other roads as may be agreed) to large administrative units rather than to small authorities as is at present the case. Attention is also drawn to a suggestion that grants should be provided from national funds towards the cost of lighting roads upon which public lighting may be considered as necessary. It is further suggested that a Committee concerned with street lighting should be advised by an engineer competent to deal with the problems which arise. It is becoming

more and more evident that the advice of such an engineer is essential in many of the points of design requiring a compromise which cannot be resolved by rules and which experience alone can decide.

CLASSIFICATION OF ROADS.

In yet another direction the committee responsible for the report has made a firm decision. This is in connection with the classification of roads dealt with in section III. The types of urban highway on which lighting is clearly required range from thoroughfares carrying a large volume of traffic to small residential roads. In the first category the lighting must be designed primarily to meet the requirements of the traffic, but in the second it is the convenience of residents and the requirements of the police which demand first consideration. Between these two extremes is a variety of types of road with no clear line of demarcation between them. The simplest classification, then, is into two groups. Such an arrangement reduces the chances of indecision when attempting to classify roads and, as the report points out, has a further advantage. If, as is recommended, the lighting for the traffic routes (Group A roads) is to be such that an ample margin of safety is provided for all road users, without the use of headlights by motor vehicles, and further, if drivers of vehicles are to be certain whether or not the lighting is intended to be adequate for their needs without the use of headlights, then a clear line of demarcation between the lighting of traffic routes and "other roads" is desirable. A division into two classes achieves this object. Group A roads have been defined above; Group B roads are defined as all other roads which the responsible authority considers should be lighted.

THE LIGHTING OF TRAFFIC ROUTES. (GROUP A).

In this section of the report, the variables which go to make up a street lighting installation (for example, height and power of lanterns, post spacing and position) are treated at considerable length. If the recommendations were abbreviated into a brief instruction, it might well be of the form, "erect the poles not more than 150ft. apart, but see that the lighting units are arranged in the right positions both on straight and curved roads; mount the units at a height of 25ft., ensure that they are of sufficient power within limits given, that they have a suitable light distribution and are well maintained." In the report, the mounting height is dealt with first and, afterwards, factors affecting the position of the lighting units, i.e., spacing, overhang and siting. In the writer's view, the correct position of light sources is an even more important factor than the mounting height, and it will therefore be dealt with first in this review.

Fig. 1.—A road employing occasional central light sources and illustrating the degree of uniformity of brightness which can be obtained.

SPACING AND SITING OF UNITS.

The position of the units includes their spacing, overhang, arrangement, and detailed siting in difficult

locations, both on bends and on straight roads, all of which are dealt with separately in the report.

The Committee, after the inspection of a number of installations, more especially some of those erected after the publication of the interim report, confirm that an average spacing of 150 feet between units should not be exceeded on straight roads. It is recognised that in order to obtain the best positions for the units at junctions and intersections, it may be necessary for this spacing occasionally to be exceeded, but 180 feet is regarded as the maximum for any one span, and it is stated that spacings even closer than 150 feet, *e.g.*, 120 feet are advantageous. On bends, still closer spacing is sometimes necessary.

In all cases the same fundamental principle is adopted, again in accordance with modern practice, that the sources shall be so sited that the bright areas on the road from each source shall overlap and cover the surface of the carriageway, without leaving dark regions between them. On straight roads the actual linear spacing is perhaps one of the less critical factors, but the maximum of 150ft. recommended agrees with the general experience that greater spacings, though they may succeed in special cases where all the other conditions are favourable, are unwise in general. Excessive spacings tend to a patchy result, dark spaces near the kerb, long shadows from vehicles, and poor conditions for the pedestrians at mid-span. The overhang of sources is a more important matter. Here the final report for once disagrees with the interim report in some ways. In the interim report it was recommended that an overhang of 6ft. over the kerb should be provided, and many installations were so made. In some instances, indeed, the recommendation seems to have been rather slavishly applied. Further experience showed that the amount of overhang was a matter for compromise between two conflicting factors. The provision of overhang reduces the dark zone which tends to form in the centre of the road, but at the same time it reduces the visibility in the region of the kerbs. The final report therefore recommends in effect that the two rows of sources should be fixed at approximately 30ft. apart, so that no overhang is used on roads 30ft. wide between kerbs, but as the width increases the overhang should increase up to a maximum of 6ft. For wide roads the wise provision is made that occasional central sources should be provided. Fig. 1 shows a road so lighted, and illustrates the degree of uniformity of brightness which can be so obtained. The carriageway in this experimental installation is not very wide, but the principle is well illustrated.

On straight roads, the arrangement most favoured by the report is the familiar staggered formation. The Committee reviews the relative merits of side and central mounting, and pronounces definitely against the latter, for reasons which have only recently come to light. Central mounting tends to reduce the visibility of the kerbs and makes junctions inconspicuous, and it also tends to invite the driver to drive near the crown of the road without fear of cross traffic. For non-cut-off sources, except where trees make its use unavoidable, central mounting is therefore deprecated.

The siting of sources on bends is a much more critical matter. Here the report contains a recommendation for the location which was, at the time of drafting of the report, quite new, and which has been confirmed by work which has since been done. In such locations, which in practice are often the rule rather than the exception, the formal arrangement of sources in staggered formation is abandoned; and each source has to be carefully sited so that from every likely viewpoint the sources appear to lie behind the important regions of the carriageway without unduly large gaps between them. Where such large gaps appear in the perspective view of the sources there will be corresponding dark zones on the road, and the report gives guidance for avoiding them, in the form of a series of angles which can be used by the designer in planning the installation. In the form given in the report, the angles are not particularly simple to use or interpret, but no doubt in their next revision of their specification by the British Standards Institution, which is charged with the task of implementing the report, the method of planning on bends and difficult situations will be further simplified. When installations are planned by the method adopted in the report, however, there is no doubt that excellent lighting results. Fig. 2 shows an example of such an installation. The sources have been so located that the angles between them subtended at the observer are all less than the values given in the report, and it will be clear that the various bright areas have overlapped well, and the corner of the bend is well shown.

The report also deals with other difficult cases of siting, such as the proper lighting of dual carriageway roads, and the siting of sources at junctions. The former constitute a new problem on which little experience has so far been gained, and therefore only tentative recommendations are made. Generally speaking, the two carriageways are to be lighted as separate roads, except when the central reservation and the carriageways are both narrow, when a single row of sources on the carriageway can be made to serve both carriageways. This again is in accordance with good modern practice, for experience has at least shewn the false economy of attempting to light dual carriageway roads either from the sides alone or from the reservation alone. The result is that either the central reservation or the outer kerbs become invisible and very dangerous. Up to the present, however, no special lighting schemes have been put into operation for these

roads to take advantage of the fact that the two tracks are each one-way roads. This gives some immediate theoretical advantages, but it remains to be seen to what extent they can be exploited. It is a problem which calls for a good deal of cautious experiment before a change from the existing well-tried systems for normal roads is varied.

The recommendations of the report for the siting of sources at junctions will probably lead to a good deal of comment. The report states that "a light source should *invariably* be placed in the main road immediately opposite a side road." This is excellent for the driver leaving the side road, but it is not calculated to reveal the presence of a side road to the driver in the main road. Furthermore, in the majority of urban areas, T-junctions and cross roads occur so frequently that the rigid application of this requirement would seriously interfere with the correct location of sources in the main road. But it is doubtless the intention of the report that the many conflicts of requirements which are bound to occur when several features, such as bends and junctions and so on, occur simultaneously, will be solved by a compromise which can only be made by a lighting engineer familiar with the local circumstances. The recommendation for the lighting of cross roads, where two main traffic routes cross at right angles, by four sources placed just beyond the junction on the near side of each of the four roads, is novel and had not hitherto been generally adopted. It will be interesting to observe the results. The recommendation which might be read into paragraph 83, in which the same principle might be taken to apply to Group B roads, would if strictly applied lead to a concentration of light sources at the cross roads in residential areas in a way which from existing practice would appear to be unnecessary and undesirable; but the intention is possibly to refer to the general rather than to the specific requirements for lighting at junctions.

Fig. 2.—Example of light planning at a road corner.

MOUNTING HEIGHT.

The height of the light sources for Group A roads has been laid down absolutely at 25ft. with the proviso that there is no need to go to the expense of altering existing installations which comply with the recommendations of the Committee except that the mounting height is about 22ft. This is a valuable standardisation for both the manufacturer of poles and the designer of lighting equipment, and the wisdom of selecting this height is also evident. Attempts have been made, which have been successful when all the conditions were favourable, to light roads with low mounted units; but in this respect also, experience has shown the inadvisability of generally adopting a low mounting height. Fig. 3 shows an installation of low-mounted units, and illustrates the small patchy bright areas which are the usual result of low mounting. On the other hand, mounting heights greater than 25ft. result in an improvement which is not commensurate with the cost, and are at an unnecessary disadvantage in fog.

LIGHT DISTRIBUTION AND POWER SOURCES.

The geometrical features of the installation are thus fairly rigidly defined; and indeed, if posts are installed of the correct height and in the correct locations, half the battle of street lighting is won. A great deal remains for the lighting engineer to do in the provision of sufficient light and its proper

distribution, but he can never compensate thereby for incorrect siting or height. The niceties of light distribution do not lend themselves to specification, and the appropriate amount of light to use must be determined by the engineer with local knowledge. In the matter of the amount of light and its distribution the recommendations are therefore, rightly, far less precise.

The power of the sources is more definitely specified than in the interim report, in which it was somewhat ambiguously stated, but the designer is still left with wide limits within which to choose.

When the light output figures are translated into approximate lamp wattages for the benefit of the electrical engineer, it is found that for a modern efficient refractor unit at a 150ft. spacing, the range given by the report is covered by 500 to 1,000 watt filament lamps or 250 to 400 watt high pressure mercury vapour discharge lamps.

Little restriction is placed upon the distribution of light from the lantern. The report distinguishes between the non-cutoff and the cutoff distributions, drawing attention to the reduced spacing which the latter type requires but deferring its criticisms of

Fig. 3.—Illustration showing low mounting units and the small patchy bright areas which usually result from low mounting.

The recommendation has been so worded as to avoid as far as possible the difficulty that any minimum figure which is quoted in a specification tends in practice to be considered as a maximum. The amount of light is quoted in terms of the total luminous output of the lantern when equipped with a source giving an output equal to its mean output throughout life; a convention which differs from the practice generally adopted by the electrical industry, but one which should not cause any embarrassment, except in so far as the light output ratio of the lantern tends to be treated as a figure of merit. Actually of course the most effective lantern may well not be the one with the greatest light output ratio; the important property of the lantern is the intensities in given directions which are provided for a given energy input. A bare lamp has the greatest total light output, but it is far from being the most effective light source.

central mounting when cutoff distributions are used until experience shall shew how far they apply in this case also. The only restriction on the distribution is aimed at preventing excessive glare, and the provisions of the clause limit the maximum intensity of the unit expressed as a multiplier of its intensity directed in specified angles near the downward vertical. This requirement appears to be entirely empirical, but will probably achieve its object so long as it is applied in its spirit. It is for example, open to the designer whose lantern has a very high maximum intensity, and therefore has too great a magnification, to decrease it by increasing the intensity at 35°—45° (for example by replacing diffusing panels by clear panels). This would reduce the magnification, but it is doubtful whether a modification of this form would reduce the glare. This is, however, one of the hard cases which make bad law.

EFFECT OF ROAD SURFACE.

The report draws attention, in the penultimate paragraph on Class A roads, to the effect of the road surface on the lighting. So important a factor was no doubt left to the end because it is not usually under the control of the lighting authority; but it is recognised that the road surface can entirely make or mar the efforts of the lighting engineer. The optical properties of road surfaces are very complex and difficult to define; they are also very variable, changing with the state of wear and of weather to a degree which makes accurate specification very difficult. But generally there are certain types of surface which usually give a satisfactory performance, and there are others which are particularly difficult to light. The report draws attention to the importance of co-operation in the selection of the road materials, and it is to be hoped that the recommendation will bear fruit.

LIGHTING CLASS B ROADS.

The recommendations for the lighting of Class B roads are rather less definite than those for Class A roads. In dividing the roads to be lighted into two classes only, the Committee has included in Class B a greater variety of roads than in Class A, and those also in which the problem to be solved is more nebulous than in the traffic routes. Problems which cannot be accurately defined cannot be accurately solved, and as is to be expected the requirements are less specific. In general they follow those for traffic routes. The mounting height is restricted to a range from 13—15ft., which has the effect of discriminating definitely between the Class A roads in which it is not expected that headlights should be necessary, and a Class B road in which they may be. The upper limit is thought by some to be too low, especially in view of the upper limit of power of the sources, which is 2,500 lumens per 100ft. as compared with the lower limit of 3,000 lumens per 100ft. for Class A roads. The average spacing for Class B roads is not to exceed 120ft., a value well below the spacings used in many residential roads at present. At bends it is recommended that the siting should follow the practice for traffic routes, though it could be argued that the requirements and mechanism of visibility in the two cases are not parallel. Similarly at junctions the same principles are to apply to both Groups. The recommendations here are rather ambiguous, and probably the best siting for junctions in both groups must await further experience. The power of the lanterns is similarly stated and the distribution similarly limited to avoid glare, a lower magnification being permitted. Many general recommendations are made in points of design which cannot be definitely specified.

OTHER RECOMMENDATIONS.

The final sections of the report deal with a variety of matters which are ancillary to the main problem, some of them of particular interest. It is recommended that light sources should not be varied at the intersection of Group A and Group B roads in order to provide a gradation between the two—contrary to a belief often expressed and seldom tried. It is also recommended that lighting, where provided, should remain alight throughout the night and not be extinguished in the small hours. A method of testing the maintenance of installations by illumination tests is recommended and it is left to the British Standards Institution to work out the details. The Committee gives due warning against the use of street lighting as anything else, such as a warning device or as a fog light, each of which requires its own specialised apparatus; and finally, it deals faithfully with the perennial propositions of inventors of new systems of lighting, which range "from slight modifications of existing practice through various less orthodox methods to schemes which are demonstrably absurd." In their view, "progress is likely to result for a considerable time to come if such efforts are concentrated upon the development of existing methods."

The report is an encouragement to those engaged in street lighting development to continue their efforts; it has removed from them some of the main causes of anxiety in standardizing what can properly be standardized, and in yet leaving them free enough to improve existing practice within the not-too-rigid framework which its recommendations form. Experience may call for some modifications in detail, but there is no doubt that the general basis of the report will act as a good foundation for some time to come.

Multi-Channel Carrier Telephone Cable.

By R. J. JORDAN, A.M.I.E.E.
Chief Transmission Engineer, Telephone Department, Pirelli-General Cable Works Ltd.

The foresight of the British Post Office in introducing considerable reductions in the tariffs of long distance telephone calls has resulted in a very gratifying public response, and has necessitated the rapid augmentation of the available trunk facilities. In this article the author briefly describes one of the most important developments of recent years—the introduction of the multi-channel carrier telephone cable—which has been largely instrumental in enabling the Post Office engineers to meet the greatly increased demand for long distance calls.

ONE, two and three channel carrier circuits on light coil loaded cable have now been working for some time, but not until the advent of the negative feed-back amplifier,[1] with its extremely flat wide band frequency response and high amplification, was it possible to consider the application of a large number of carrier channels to unloaded cable circuits. The unloaded cable circuit is ideal for telephony over very long distances by reason of its extremely high velocity of transmission, but the relatively high attenuation at carrier frequencies necessitates shorter repeater sections as compared with coil loaded circuits. Echo suppressors on long four-wire circuits are obviously no longer needed, and the proven greater stability, as compared with voice frequency circuits, together with better frequency response in the speech frequency band are important factors in the adoption of multi-channel carrier systems.

A considerable amount of experimental work on the problem was done in America and a 12-channel carrier system was evolved making use of normal unloaded telephone cable pairs for transmission. As a result of these experiments, and without doubt urged by the necessity of rapidly providing trunk facilities, the British Post Office, with pioneer outlook, had the first 12-channel carrier cable system installed between Bristol and Plymouth. The success of this naturally prompted them to extend the system considerably. It was decided, therefore, to establish a 12 channel carrier cable network, and orders were placed with the G.E.C. for the manufacture and installation of a system extending from London to Leeds with ultimate extension to Carlisle.

The 12-channel system designed at the G.E.C. Telephone Works is essentially a four-wire system necessitating the use of two cable pairs or two physical circuits, one pair for each direction of transmission. High amplifier gains on four-wire circuits are limited by near-end cross talk arising from mutual admittance and impedance couplings between circuits having opposite directions of transmission. This limitation has been practically overcome by the use of two separate lead covered cables for each direction of transmission so that it is possible to make use of the full gain (which is of the order of 60 decibels) of a three stage feed-back amplifier.

The problem as viewed from the equipment side has already been described.[2]

Fig. 1.—Sample of special 24-pair 40 lb. conductor carrier type cable.

THE CARRIER CABLE.

A special carrier cable has been designed having a pair capacity of approximately 0·058 mfds. per mile (as compared with normal telephone cables having a capacity of 0·066 mfds. per mile), and great care was taken in the selection of the quad twists or lays so as to minimise both mutual electrostatic and electromagnetic inter-circuit couplings.

The cable consists of 24 pairs of 40 lbs. air spaced paper insulated copper conductors, made up in quad formation. A section of this cable is shown in fig. 1. The quad formation was decided upon because of its essentially uniform construction, as compared with pair type, as uniformity in carrier cable construction is of prime importance.

Careful consideration was also given to the problem of irregularities

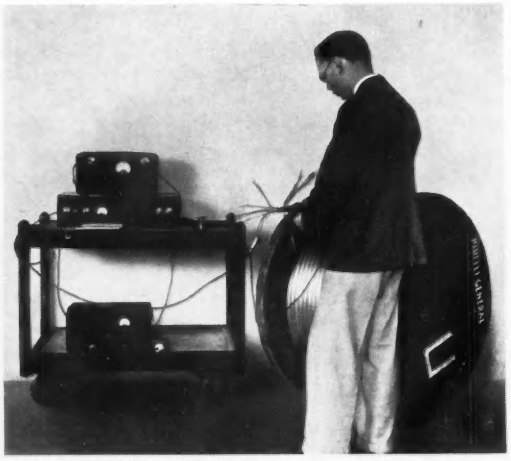
1 A description of the negative feed-back amplifier by L. I. FARREN of the G.E.C. Research Laboratories appeared in the "Wireless Engineer" for January, 1938.

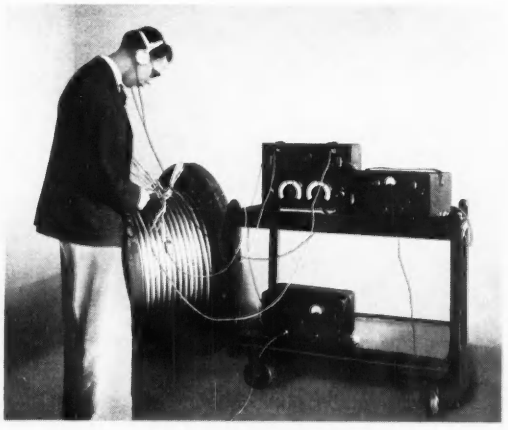
2 G.E.C. Journal, Vol. IX., No. 1.

resulting from eddy current losses due to metallic masses in proximity to the cable pairs. For example, the proximity of the lead sheath to the cable pairs not only causes these pairs to have much higher attenuation values at carrier frequencies than pairs more removed, but also accentuates the complexity of the electro-magnetic inter-circuit couplings.

Experimental investigation has shown that there is a definite relationship between the distance of the lead sheath from a pair of conductors and the distance between the centres of the conductors of a pair, for which the losses due to eddy currents in the sheath can be considered negligible.

The cable[3] is manufactured in lengths of about $\frac{1}{10}$ mile and every length is covered with pure lead on a new type of lead extruding machine which is continuous in operation and ensures that there will be no defects in the lead sheath.





Figs. 2 (a) and (b).—Magnetic coupling measurements being made on carrier type cable.

TESTS ON FACTORY LENGTHS.

The routine electrical measurements made in the factory on all trunk telephone cable lengths are :—

(1) D.C. Tests.
   (*a*) Conductor resistance and resistance difference between wires forming a pair.
   (*b*) Conductor insulation resistance.
(2) A.C. Tests. (Voice frequency).
   (*a*) Mutual capacity (between wires forming a pair).
   (*b*) Capacity unbalance (capacity couplings between pairs in the cable).

Whereas for normal type telephone cables used for voice frequency transmission, it is only necessary to take into consideration the magnitude of electrostatic couplings between pairs in a cable length, the extension of the frequency range has emphasised the importance of electromagnetic couplings and has necessitated careful systematic measurements of electromagnetic components between all combinations of pairs in every carrier cable length manufactured. These electromagnetic couplings are not pure couplings, but are complex in nature due to skin effect and eddy current losses in neighbouring circuits and surrounding metallic masses. The carrier cable has been designed to reduce these secondary effects to a minimum.

Special carrier frequency apparatus was designed and developed at the G.E.C. Research Laboratories for the measurement of the complex magnetic couplings and figs. 2a and 2b show measurements actually being made on a drum length of carrier cable in the laboratory. These measurements are all made at 5 kC and couplings of the order of 10^{-10} henry can be detected. A further check on the uniformity of manufacture is obtained by frequent measurements of the primary constants of the cable pairs at 60 kC. The secondary constants, attenuation, phase and characteristic impedance, are determined by calculation from the measured primary constants.

INSTALLATION.

The installation of these carrier cables in general follows normal telephone cable installation practice, and no radical changes from normal practice are entailed in the routine testing in the field apart from greater care in testing and in the reduction of capacity unbalances to much lower limits. The two cables (go and return) are pulled together into the same duct in factory lengths of approximately 1/10th mile. Each factory length is then tested for capacity unbalance at voice frequency and selected joints are made to reduce the capacity unbalances to a minimum

3 G.E.C. Journal, Vol. VII., No. 2.

in sections of approximately 0·4 mile. Four such balanced sections are then jointed together by selected joints into balanced sections of approximately 1·6 miles. Each balanced section of 1·6 miles is then air pressure tested to prove the cable sheaths and joints free from defects.

The systematic reduction of capacity unbalances in each 1·6 mile section having been accomplished, these sections are jointed together, wire to wire, in corresponding quads, leaving the middle joints in each half repeater section. These joints are made quad to quad but a wire cross in one pair of a quad may be introduced to give improvement in distant-end cross talk, as a result of measurements made on the half repeater section at 5kC. The cables comprising a complete repeater section length as finally installed, consist of two half sections. At approximately the middle of the section the four cables are terminated with 24 circuit test tablets in a small hut which houses special equipment for distant-end cross talk balancing. A typical condenser balancing hut is shown in fig. 3. The cable circuits are made continuous from repeater station to repeater station, from test tablet to test tablet, by special lead covered twin conductors and the wiring of the condenser balancing equipment at the huts. Fig. 4 shows the incoming and outgoing cables at one of these huts, and indicates also the test tablet terminations. The cables at the repeater stations are terminated in a similar manner. Fig. 5 shows the permanent wiring of the condenser balancing rack. This network of wires enables condensers to be connected easily between any one pair of wires and a wire of any other pair.

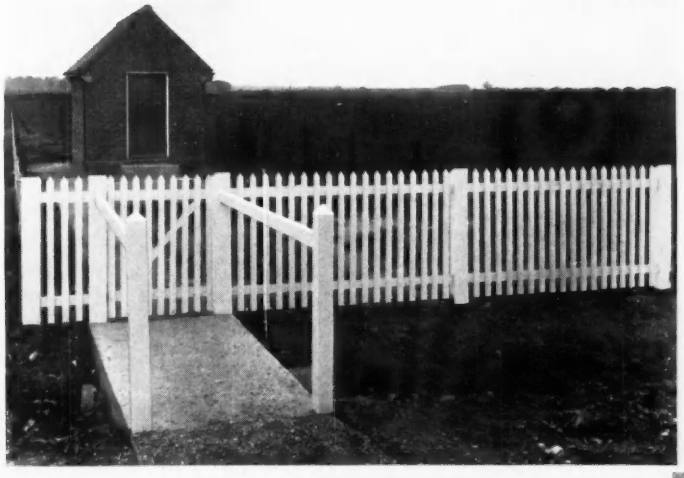


Fig. 3.—Exterior view of hut housing condenser balancing equipment on the Cambridge-Leeds route.

REPEATER SECTION TESTS.

When the installation of the cable and the jointing in a repeater section is completed, the most important problem to be tackled is that associated with the installation of the condensers at the balancing huts and the adjustment of them to give maximum distant-end cross talk attenuation. Having considerably increased the near-end cross talk attenuation between opposite going circuits by using two separate cables, it is only necessary to consider the distant-end cross talk between circuits having the same direction of transmission. The distant-end cross talk between two circuits increases rapidly with frequency and it has been found that efficient reduction of cross talk between any two circuits can be attained by connecting simple adjustable condensers between selected wires of the two circuits considered. Consider two pairs A and B in a cable and let a source of EMF be applied to pair A at the remote end of the circuit. Due to mutual coupling between the two pairs energy will be transferred from A to B and will appear as a voltage across the near end of pair B. By the introduction of capacity in the form of a small condenser between a wire of pair A and a wire of pair B, this induced voltage at the near end of pair B can be reduced to a minimum. This, very simply, is the principle adopted for the improvement of distant cross talk attenuation. It does not matter at what point along the length

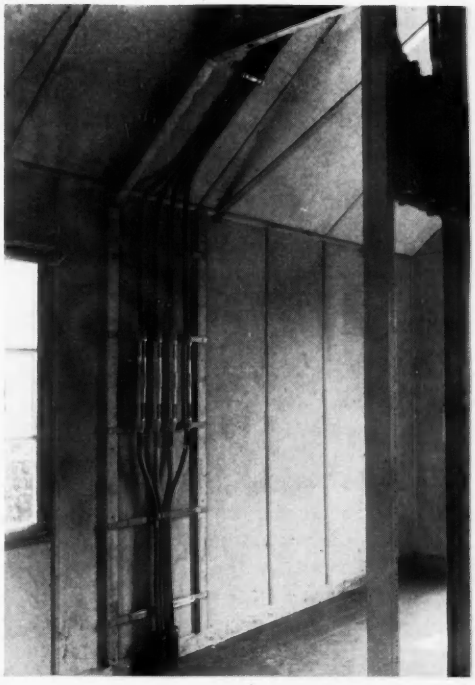


Fig. 4.—Incoming and outgoing terminated carrier cables at a typical condenser balancing hut.

of the line that the compensating capacity is introduced since the elemental quantities of energy transferred from one circuit to the other by the distributed mutual couplings are practically all in phase, having effectively traversed the same electrical

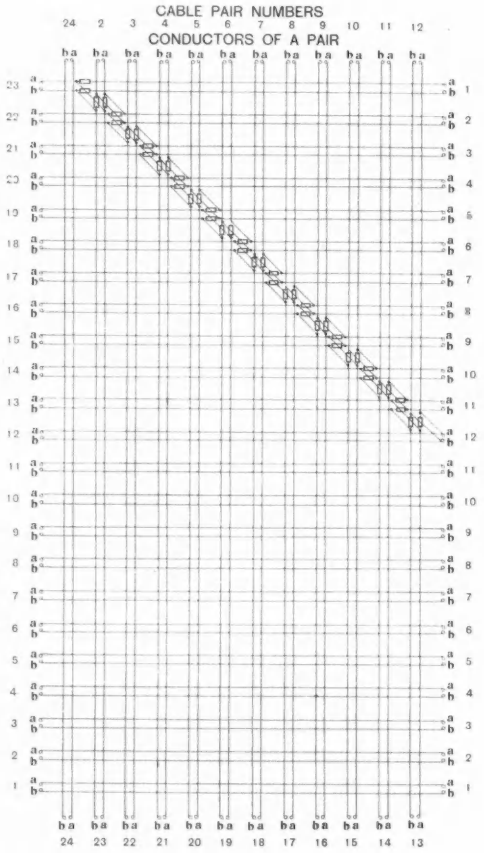

CABLE PAIR NUMBERS
24 2 3 4 5 6 7 8 9 10 11 12
CONDUCTORS OF A PAIR
ba ba ba ba ba ba ba ba ba ba ba ba
23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
a b
ba ba ba ba ba ba ba ba ba ba ba ba
24 23 22 21 20 19 18 17 16 15 14 13

Fig. 5.—Wiring network of condenser balancing panel for 24-pair carrier cable.

path. American practice favours the use of specially designed mutual inductances and condensers for this purpose, but there appears to be little to justify this. From the point of view of the installation, the condenser would seem to be a much more simple and equally satisfactory device.

The object of having condenser balancing racks at the mid-section was to avoid possible reflection trouble had they been installed at the terminals of the repeater sections. It has now been decided, however, from the satisfactory results obtained that the condenser balancing equipment will in future be installed with the receiving terminal equipment at the repeater stations. The measurements and condenser adjustments are made at 60 kC which is the top frequency of the 12 channel carrier frequency band. The condensers used are air dielectric and of the differential type, having a maximum value of 200 picofarads. Since as already mentioned the couplings are not pure but complex, to obtain a reasonably high level of cross talk attenuation a complex balance of the form shown diagrammatically in fig. 6 can be used instead of a simple condenser. Fig. 6 also shows improvement curves obtained at 60 kC for different values of the components of a typical complex balance. Experiments have shown that improvements obtained using condensers only, adjusted at 60 kC, hold very well over the transmission range. The additional refinement of the complex balance has only been found necessary in very special cases, and it has been generally found that condensers alone will suffice.

Since there are 24 pairs in each cable, the total number of combinations of pairs is 276 which means that at each balancing hut there are two condenser racks, one for each cable, containing 276 balancing units. Fig. 7 shows a photograph of the type of balancing condenser used. The distant-end cross talk attenuation improvement obtained by these means is of the order of 10 decibels. It is claimed that by using small compensating mutual inductances improvements of the order of 16 decibels can be obtained, but the additional complication as compared with the simple condenser unit would not appear to justify its adoption.

The following summary is given for results at 60 kC on one cable in a typical repeater section before and after condenser adjustments were made.

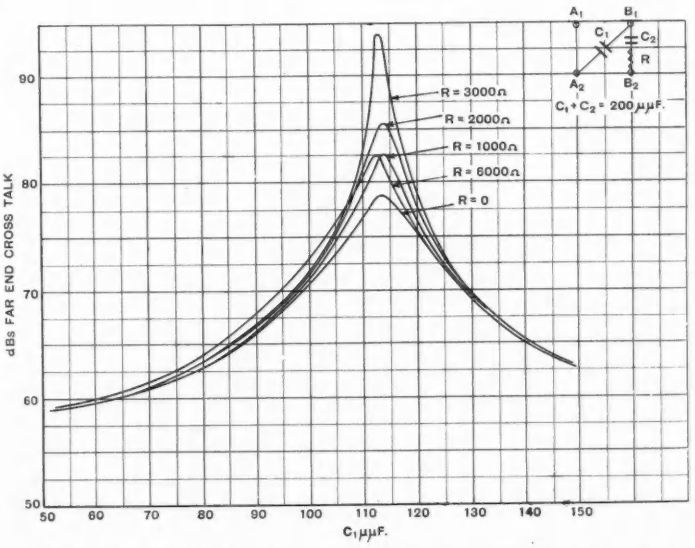


Fig. 6.—Typical distant end cross talk attenuation improvement curves obtained with complex balances at 60 kC.

Distant-End Cross Talk Attenuation at 60 kC (Signal-Noise Ratio).

	Decibels.	
	mean	*min.*
Before balancing	72·7	60·0
After balancing	86·9	80·0
Average improvement ..	14·2	—

After completion of the distant-end cross talk balancing, near-end cross talk measurements are made between pairs in the same cables and between pairs in separate cables from both ends of each repeater section and at specific frequencies up to and including 60 kC.

The great advantage of having the two directions of transmission in separate cables is indicated by the extremely high levels of near-end cross talk attenuation measured between such separated circuits. These levels are of the order of 152 decibels at 60 kC and indicate very clearly the effectiveness of the screening given by the cable sheaths. The screening effect becomes even more pronounced as the frequency increases.

The near-end cross talk attenuation between two separate cables can be shown to be given by—

$$20 \log_{10} \left| \frac{2P}{\epsilon^{-x}(1-\epsilon^{-2Pl})} \right| \text{ decibels.}$$

where P and X are the propagation constants for the cable pair and the cross talk path respectively and "l" the length of the circuit. It can be clearly seen that as the propagation constant of the transverse coupling path increases, an increase in the near-end cross talk attenuation occurs.

Fig. 8 shows a photograph of a special carrier frequency cross talk measuring set designed and developed by the G.E.C. Research Laboratories for accurately measuring attentuation levels down to 180 decibels over the carrier frequency range.

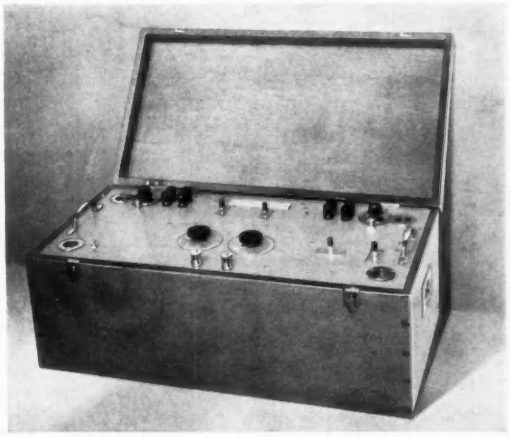


Fig 8.—Carrier frequency cross talk measuring apparatus.

IMPEDANCES AT 10 AND 60 KCS.

Circuit.	London-Broxbourne.			Broxbourne-Barkway.			Barkway-Cambridge.		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
10 kc/s.									
Cable 1	161·6 /14° 49′	161·0 /15° 16′	163·0 /15° 4′	162·2 /15° 22′	161·4 /15° 20′	162·7 /15° 41′	162·7 /15° 25′	161·4 /15° 14′	162·9 /15° 25′
Cable 2	162·2 /15° 15′	161·7 /15° 10′	162·8 /15° 18′	162·0 /15° 37′	161·3 /15° 32′	162·7 /15° 35′	162·3 /15° 23′	161·5 /15° 0′	162·9 /15° 30′
60 kc/s									
Cable 1	144·9 / 4° 44′	142·8 / 4° 48′	146·9 / 5° 40′	144·3 / 5° 3′	142·3 / 4° 58′	146·6 / 5° 19′	143·6 / 5° 24′	141·3 / 5° 21′	145·4 / 5° 32′
Cable 2	143·8 / 5° 23′	142·2 / 4° 55′	146·8 / 4° 55′	144·2 / 5° 23′	142·4 / 4° 14′	146·6 / 5° 1′	143·6 / 6° 0′	140·9 / 5° 44′	145·1 / 4° 57′

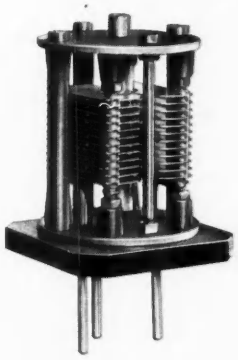


Fig. 7.—Differential air condenser used for distant end cross talk balancing.

Transmission measurements are made on all circuits in each repeater section over and beyond the working frequency range. In the case of impedance measurements it is necessary to make these from both terminations of each repeater section. A typical impedance frequency characteristic for these carrier cable circuits is shown in Fig. 9.

On this page is given a summary of impedance measurements on three repeater sections of the London-Cambridge carrier cable system at 10 kC and 60 kC. It will be noticed that the deviations from the mean impedances are extremely small which indicates the degree of uniformity in manufacture.

It is important that these deviations should be small in order to avoid undesirable reflection losses when working with terminal apparatus.

Circuit attenuation is measured on all sections over the carrier frequency range and a typical attenuation-frequency characteristic is shown in fig. 10. This curve is very nearly a straight line over the carrier range which facilitates the design of the line attenuation equalizer networks. Again it will be observed from the summary given below of measurements made on the three repeater sections previously mentioned, that the deviations from mean values of attenuation at 60 kC are very small. This uniformity is in part due to the mixing of the circuits during installation.

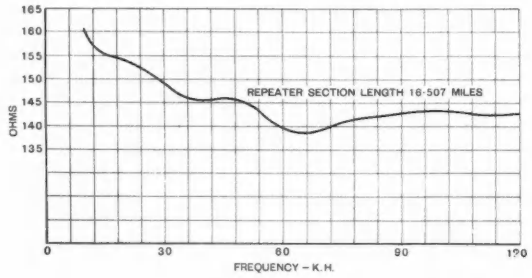


Fig. 9.—Typical repeater section impedance-frequency curve.

Resulting from the excellent quality of these carrier cables further experiments and measurements at higher frequencies have indicated the practicability of extending the 12-channel carrier system to 24 or even 36 channels. Again, with the possibility of raising the input transmission level to the repeater sections, it has been suggested that repeater section lengths, now limited to an overall transmission loss of 60 decibels at 60 kC, may be increased to an equivalent of 70 decibels. As the frequency range is increased so the quality of the cable, which forms the vital link of the transmission system, must improve, and the demands on the manufacturer become more and more stringent.

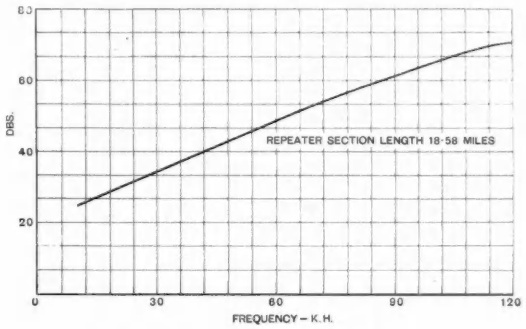
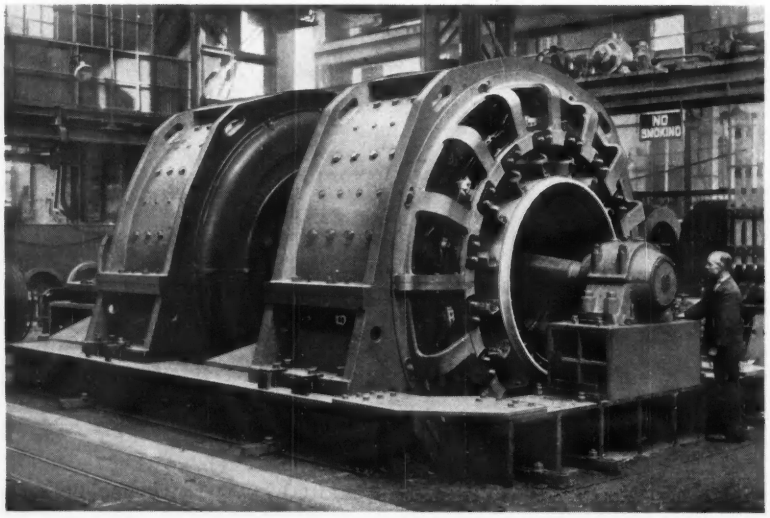


Fig. 10.—Typical repeater section attenuation-frequency curve.

ATTENUATION AT 60 KCS.

Repeater Section.	Attenuation at 60 kc/s. decibels/mile.			
	Cable 1.		Cable 2.	
	Max.	Mean	Max.	Mean
London–Broxbourne ..	2·57	2·56	2·57	2·56
Broxbourne–Barkway ..	2·58	2·58	2·58	2·58
Barkway–Cambridge ..	2·53	2·52	2·54	2·54

D.C. Winding Equipment for a S. African Gold Mine.



Two 2,750 h.p. D.C. winder motors erected at Witton Engineering Works prior to despatch to West Spaarwater Gold Mining Co., Ltd.

Recent Progress in Power Rectifiers and Their Applications.

PART II.

By W. G. THOMPSON, Ph.D., B.Sc., A.M.I.E.E.
G.E.C. Mercury Arc Rectifier Works, Witton.

This is the second part of an article which was read by the author before the Institution of Electrical Engineers. The first part appeared in the previous issue of the G.E.C. Journal (Vol. IX, No. 2.)

General features of rectifier equipment are considered, together with some aspects of rectifier auxiliaries. The scope and performance of rectifier installations are also indicated, special reference being made to railway electrification, high voltage working and the applications of grid control.

Finally, some suggestions of the possible trend of future developments are given.

5. GRID CONTROL.

IN reviewing the progress made in connection with the so-called "grid control" for rectifiers, it must be admitted that the extent to which grid control has been applied in practice has fallen considerably short of the experimental and theoretical possibilities. As a means of controlling the output voltage of the rectifier in a continuously smooth manner, grid control appears to be admirable. On the other hand it involves several important practical points; first the suitability of the grid control gear, and secondly the cost of the filter gear necessary to cope with the large amplitude harmonics produced in the voltage output wave, when the ignition or the start of the conducting period is retarded. Another point is the poor power factor resulting when operating at reduced voltage under grid control conditions. So far as the mercury arc rectifier is concerned, grid control has been limited to the inhibition of the striking of the power arc. It is true, that on a small experimental scale it has also been found possible to stop the arc discharge once it has been started, but so far as the author is aware there have been no major practical developments of this idea. On paper there are many attractive forms of grid control to produce certain desired characteristics, and methods of frequency changing, but in actual practice it would appear that this application may be limited to the voltage regulation of rectifiers, inversion in connection with regenerative breaking, and arc suppression.

The Grid Controlled Rectifier.

The grid controlled rectifier is of normal construction except for an extra insulated grid situated immediately in front of each anode and connected to a source of negative d.c. potential which persists except when the positive debiasing influence is applied. There still remains considerable scope for research into the mechanism of the action of the control grid in relation to the arc stream, but much more is known about the grid characteristics and their behaviour under given conditions of rectifier loading and temperature. It is known, for example, that there is an optimum temperature at which the grid is able to exercise its maximum shielding influence on the anode for the particular value of voltage bias applied. Furthermore, under extreme overload conditions the factor of safety on the grid control also diminishes unless the bias is suitably increased. The object of successful design is to adjust the stable portions of these characteristics to correspond with the working range of temperature and load on the rectifier.

It has been found advisable in the interests of precision to apply the debiasing voltage in the form of a steep fronted wave, as the alternative method of steadily increasing the amplitude of the positive bias may lead to uncertain timing of the ignition of the anodes. A steepness of 60 volts per electrical degree is usually adequate. Various suggestions have been made as to the ideal profile of the positive impulse to be applied to the grid, and theoretical reasons have been advanced for prolonging the impulse to cover nearly all of the burning period for a given anode, the train of the wave being shaped away to cause a gradual transition from the positive to the negative bias condition. Practical experience has shown, however, that whilst it may be an advantage to prolong the impulse in certain circumstances, the working conditions, and in particular inverted operation, demand that the duration of the positive bias be kept within reasonable limits.

Voltage Regulation.

In the case of voltage regulation, the arrangement is that for the normal voltage the ignition of the rectifier must be slightly retarded; to increase the

direct current voltage, the ignition of the rectifier must be advanced, and to lower the voltage, the ignition must be further retarded. Various methods of effecting grid control have been devised which may be grouped as follows :—

1. Those using synchronously rotating mechanical parts, such as commutators or contact makers.
2. Those employing saturated transformer or similar wave peaking devices.
3. Those using condenser discharging circuits.
4. Circuits employing thermionic devices.

In order to achieve the desired voltage regulation, it is necessary to vary the instant at which the impulse is applied. This can be carried out in three ways,

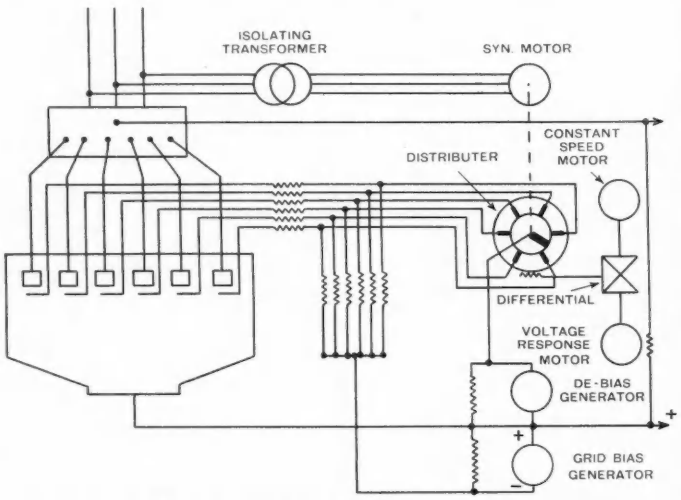


Fig. 9.—Grid-control circuit using synchronous distributor and voltage-regulator differential.

namely, by using phase shifting transformers, altering the synchronous position of the rotating mechanical gear, or controlling the grids of the thermionic control device, depending upon which system is in use. All these methods have been tried out under practical conditions, though each has its distinctive features requiring careful design. It is also necessary to recognise the true nature of the problem of grid control. Many devices have been suggested in this connection, but the difficulty lies in producing the proper working characteristic. Most schemes devolve essentially into one of voltage regulation, rather than that of compounding. The inherent difficulty is that the curve of the mean output voltage of the rectifier under control conditions is a cosine characteristic, and it is practically impossible to devise simple means whereby the phase shift actuated by the load can be translated into terms of a suitable voltage current characteristic. We have also to distinguish between those cases where the rectifiers are operating independently and where they are operating in parallel with other equipments, such as rotary converters, etc. The obvious solution appears to be to provide an external shunt characteristic to suit the rectifier since the inclusion of voltage regulating means and relays results in the action not being absolutely instantaneous where compounding is attempted.

Inversion.

Inverted operation of the mercury arc rectifier is effected by changing over the polarity; the current must still flow in the same direction through the rectifier and is made to flow by the impressed d.c. voltage against the back e.m.f. provided by the a.c. phases in their proper anodic sequence. An a.c. voltage supply is necessary for wave forming and the function of the grid control is to regulate the transference of the arc from one anode to the next at the proper instant. The same methods of control have been applied to the inverter as to the rectifier, the only difference being slight modifications to the characteristics and a change in the phase position of the ignition point.

Unfortunately, the inverter is still handicapped by the fact that it injects a.c. current at a leading power factor into the a.c. network, and as a result its usefulness is practically confined to regenerative braking in traction and rolling mill operation. Another difficulty is the polarity changeover required. Where it is possible to regenerate to schedule, use can be made of changeover switches, but cases of emergency braking can only be dealt with by having a second rectifier permanently reverse-connected across the d.c. bus-bars. By this means the substation can supply or alternatively absorb energy in rapid sequence if so called upon.

Any of the four main types of grid control schemes can be adapted to suit voltage regulation or inversion requirements. Circuits have been recently devised to enable automatic adjustment in the slope of the operating characteristic, the change-over point, and the limits of loading of the inverter.

Considering now examples of types of control gear, the operation of the synchronous distributor has been frequently described in the technical press, and the means by which the positive impulses are applied to the negatively biased grids can be seen from figure 9. Some practical notes may, however, be of interest. The most suitable form of distributor is that of a small commutator having two diametrically spaced live segments; the remainder of the segments are idle and merely serve to avoid uneven wear. The brushes are suitably grouped around the commutator and advance or retard of the ignition is obtained by brush rocking. This method has proved more convenient than adjusting the synchronous

position of the commutators because of the low inertia of the brush gear, the slight friction is also sufficient to prevent hunting, and overhauling can be avoided by the fitting of slipping clutches. A steady negative bias of about 100 volts and positive peaks up to 300 volts are used. Using good quality brushes and avoiding sparking at the commutator, the method is perfectly reliable and the brush wear slight. Level compounding can be carried out by making the device responsive to a voltage regulating relay, but for parallel running and inverted working voltage balancing devices involving electrical or mechanical differentials are used.

The application of a peaky wave transformer to grid control (fig. 10), calls for a means of adjusting the phase of the voltage impulse to give the requisite variation of the ignition instant for voltage regulation, and the phase shift needed when changing over to inverted operation. One such system employs a phase shifting transformer in series with the winding of the wave peaking transformer. The rotation of the phase shifting transformer can be achieved by means of a direct current spring-opposed torque motor whose armature is supplied at constant voltage while its field carries some given amount of the output of the rectifier. Any desired characteristics can be arranged by connected rheostats in series with the motor armature, whilst further flexibility is also possible with the aid of additional shunt windings and screw adjustments. Due to the inertia of the moving parts there is a practical limit to the speed of response of such control and to avoid hunting, the arrangement needs to be suitably damped. It will be understood that there are various possibilities similar to the scheme outlined above, such as loading the torque motor against an opposing torque motor, or achieving phase shift by means of a saturating winding. Proper regard must be given in each case to the control means having the desired characteristics.

The thermionic method of control involves the use of radio valves and gas filled discharge devices. At one time their application was questionable in view of the high factor of safety required, but to-day, the standard of performance of such devices has improved enormously and on the Continent[11] practical use has been made of this method of control for rectifiers up to 10,000 amperes. It is considered that provided the valves are given a short preliminary ageing and if two or possibly three are used in parallel, the conditions indicated from the statistical records of the lives of such valves would be amply covered, and the probability of the failure of the control gear is thus practically nil. The thermionic method may well be the most satisfactory where very high speeds of response to fluctuating conditions are required. In addition there is a wide range of choice in the design of the control circuits, both from the points of view of the impulse shape and the voltage regulation. The voltage impulse can be applied to the rectifier grid either by utilizing the voltage drop across a resistance in series with the anode cathode circuit of the valve or by means of a transformer in the anode circuit.

Arc Suppression.

The efficacy with which arc suppression can be carried out depends first upon the nature of the fault, secondly upon the type of load on the d.c. side of the rectifier, thirdly upon the speed with which the negative bias can be applied to the grids, also if in

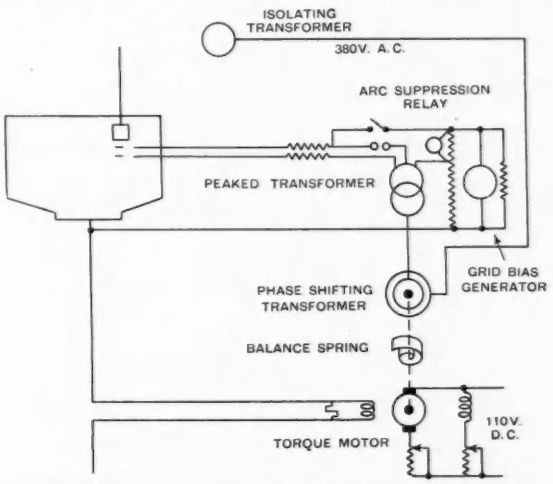


Fig. 10.—Grid-control circuit (shown in simplified form) using peaked transformer and torque motor.

use, the positive impulses interrupted, and fourthly upon the effectiveness of the grids as screening and deionising devices. In order to energise the grids rapidly, use is made of a high speed relay, generally of the form of a miniature high speed contactor. The essential features are a high speed response combined with non-chattering of the contacts. The time taken for this type of relay to operate is about 2 milli-seconds. An alternative method of control, also successful, is to use thermionic devices of the gas-filled relay type which are almost instantaneous in action.

The suppressing action has been studied with the aid of the cathode ray oscillograph, and tests have shown that whilst artificially induced backfires can easily be suppressed under light load conditions (see fig. 11), the suppression with the rectifier on heavy overload is more difficult and requires careful design of the grids and the relay. The whole operation may take 0·02 seconds. One reason for the difficulty in dealing with heavy overloads on backfire is the shape of the grid characteristic. This difficulty

11 H. Jungmichel and E. Kottenham "On the Control of Large Rectifiers with Valve Regulators." Siemens Zeitschrift, 1937, Vol. 17, p. 49.

H. Anschütz and M. Stöhr "On the Adaptation of Converters to Motor Control." A. E. G. Milleilung, No. 6, June 1937, p. 208.

can be overcome by keeping the anode current loading low, although it may mean building the rectifier with twelve and sometimes eighteen anodes per cylinder. A further point is that in the event of a heavy direct current feed back the alternating current wave with respect to one anode may be completely asymmetrical, in which case recourse

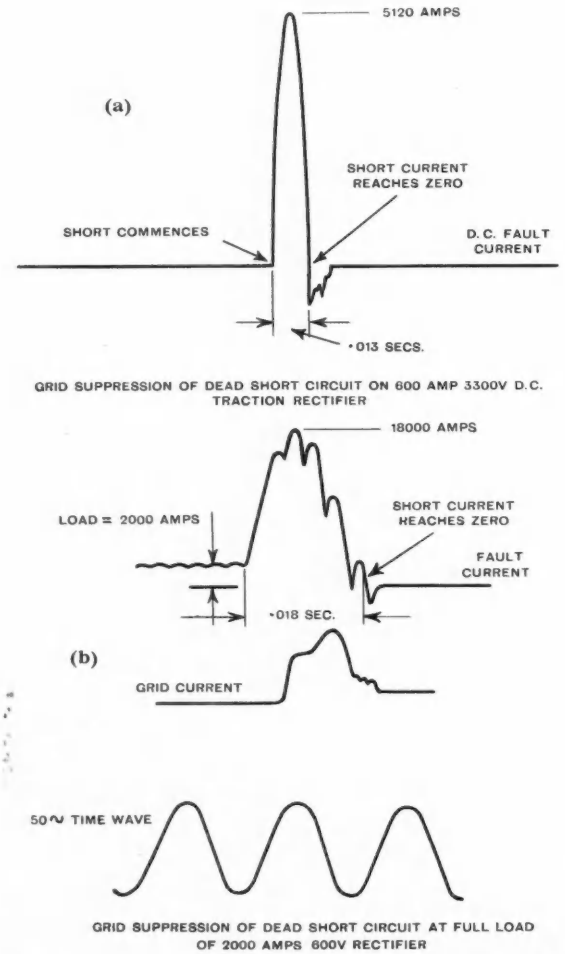


Fig. 11.—Fault current suppression by control grids.

(a) Grid suppression of dead short-circuit on 600 amp. 3300 volt (d.c.) traction rectifier.

(b) Grid suppression of dead short-circuit at full load of 2000 amp. 600 volt rectifier.

to high speed circuit breakers is inevitable. Most d.c. circuits whether they operate rotating machinery, electrolytic plant or have other rectifiers on a common d.c. bus-bar are capable of feeding into a faulty rectifier, and the number of cases wherein the high speed breaker can be dispensed with, with impunity, are comparatively few. Finally, although the advantage of limiting the fault current is recognised, and arc suppression is becoming a common feature of mercury arc rectifiers, it may involve a higher arc drop under normal conditions and a slight loss of efficiency.

6. CONSIDERATION OF RECTIFIER EQUIPMENT.

Throughout the various stages of development the rectifier has had a marked influence on the design and rating of the equipment directly associated with it, and a few passing remarks thereon may be of interest.

On the high tension side of the rectifier transformer the main switchgear is required to have a higher rupturing capacity than would normally be used for a plant of the same nominal kVA as the rectifier transformer. The factors arising under fault conditions combine not only to increase the duty on the breaker, but demand a higher dielectric recovery rate and in some cases this has resulted in an increase of 50 per cent on the mVA rating of the switchgear required.

The design of the rectifier transformer is dependent upon several features. On the one hand the working conditions demand a robust transformer, but on the other hand the multiplicity of phases on the secondary side combined with the numerous crossover connections needed for the maximum utilisation of the active material add considerably to the difficulties of insulation and mechanical bracing. In practice such problems have been overcome and effective and reliable rectifier transformers can be produced. Various problems still remain and brief mention will be made of their more outstanding points.

The harmonic problems may be divided into two groups, these being the direct current voltage ripple and the alternating current harmonics. Up to the present the provision of smoothing gear in the shape of resonant shunt circuits, or alternatively the adoption of a 12 phase system of connections has proved adequate to meet the case as far as the direct current side is concerned. Incidentally a smoothed 6 phase circuit has actually less ripple than an unsmoothed 12 phase equipment. These practices are well established and have already been discussed in many publications. On the a.c. side the position is not quite so well defined. The conditions giving rise to difficulties with a.c. harmonics are well known, but fortunately in practice, troubles have been confined to a few isolated cases. At the same time the provision of a.c. smoothing equipment is neither economic nor desirable and alternative means have to be used to suit each particular case. Numerous theoretical circuits have been devised to produce favourable operating conditions but in any practical scheme the working of the interphase transformer and the necessity of maintaining correct phase commutation must always be borne in mind.

The outstanding problems associated with the a.c. side of rectification are :—

1. Wave form distortion.

2. Resonant effects of a.c. harmonics.
3. Interaction of rectifiers whose phases differ in number.
4. Interference with communication circuits.

Wave form distortion has been suggested as a potential source of heating of the alternators in the central station supplying the rectifiers when the total kW of such load becomes very large. As a result of the successful operation of the Berlin City Railways with their 170,000 kW of plain 6 phase rectifiers it is realised that in practice the effect is much less than calculation would indicate.

One or two isolated cases of resonance of high tension lines with rectifier harmonics have occurred, a particular case being that of a 25 mile 100 kV line resonating with the 11th and 13th harmonics. Fortunately such occurrence is extremely rare and only takes place where the natural frequency of the line is low and is usually confined to one harmonic. Two solutions of the problem are available. The first is an increase in the number of phases so as to eliminate the resonating harmonic, and in the above mentioned case it was necessary to proceed to 24 phases to eliminate the 13th harmonic.

The second method is to arrange a phase displacement of the harmonic from one of a pair of rectifiers to cancel out the corresponding harmonics of the second rectifier. This phase shifting arrangement, whilst requiring an additional transformer, does enable the normal design practice to be followed in connection with the rectifier transformers.

The question of increasing the number of phases to produce a smooth output on the d.c. side or to eliminate a particular harmonic on the a.c. side involves the problem of the stability of rectifiers using more than 12 phases. Even with twelve phases there is the possibility of the equipment reverting to 6 phase operation or the intermittent firing of certain anodes where the a.c. wave is badly distorted by the 5th and 7th harmonics which, by the way, may arise from transformer saturation independently of any rectifier load. The root of the problem is the small commutating e.m.f. available when the number of phases is large. To overcome this difficulty circuits giving a steep fall of anode voltage towards the end of the burning period have been proposed, but again this tends to introduce a percentage of 5th harmonic into the voltage wave and its general adoption is hardly likely to meet with favour. The ideal is to provide the maximum of stability for the rectifier with the minimum of disturbance to the system. There is little doubt that for stability the six phase case is ideal, and in view of the general experience, they can be accepted as satisfactory. If necessary, however, the position can be made still more safe by the use of alternatively star and mesh connected primary windings of rectifier transformers on the same system.

A few cases of interference with communication circuits due to rectifier harmonics are recorded, but, with the exception of one or two isolated instances, they have not proved serious and normally no special precautions beyond the usual smoothing gear are considered necessary.[12]

The influence of grid control upon rectifier equipment is marked in many directions. In the first place the additional control gear per phase makes it very desirable to limit the number of phases in the rectifier, but on the other hand the smoothing gear requires to be larger to deal with the "saw-tooth" wave form. The overlapping effect of the interphase transformer and its voltage wave shape in relation to the incoming phase together with the duration of the positive controlling impulse needs attention. A more serious aspect of grid control is that of its influence on the power factor, for example a voltage regulation of 15 per cent may involve a lag in the power factor down to 0·8 and should long periods of operation at reduced voltages be contemplated, tap changing gear is advisable and the grid control relegated to merely smoothly regulating the voltage between one tap change and the next.

Another aspect of rectifier transformer equipment is the placing of the auxiliaries such as the interphase transformer and the various choke coils. In the case of units of large outputs associated with water-cooled rectifiers, there is usually only the interphase transformer housed with the main transformer in the one tank. With the smaller equipments there are two schools of thought, one favouring the separate disposition of the various components such as the anode chokes, auxiliaries, etc.; the other associates the auxiliaries with the main transformer in the one tank. Such practice is conducive to apparent neatness in the substation and the cubicles, but at the expense of the internal simplicity of the transformer.

The problems of temperature control and improvement of light load efficiency of the air-cooled rectifiers has been further advanced through the more general adoption of fan speed control chokes which regulate the amount of cooling and power input to the fans in proportion to the load on the rectifier. The resultant saving compared with constant speed fan equipment is to a large extent dependent upon the load factor of the rectifier.

In the case of the air cooled rectifiers, both of the all metal or the glass construction, in the event of a backfire the rectifier must be isolated with all speed. Anode fuses have been found to give effective protection in this connection, and these have undergone a steady change in recent years and

12 H. JUNGMICHEL: "Harmonics, Ripples and Interference Voltage of Rectifiers," Elektrotechnische Zeitschrift 1937, Vol. 58, p. 417.
W. GERBEN and H. KÖLLIKER: "H. F. Wireless Interference by Rectifiers," Bulletin Schweizerischer Elektrotechnischer Verein, No. 25, p. 654.

are now designed so that they do not fuse under ordinary forward short circuit conditions, but only in the event of a backfire. Both the chemical filled and the oil immersed types are used, but their length is considerably increased so as to render them capable of dealing with any direct current component in the backfire current. Actually these fuses, made in ratings up to 250 amperes, are a comparatively costly item and their frequent replacement would be most uneconomical and the fact that they so rarely fail is a tribute to the reliability of the modern air-cooled rectifier.

Of the many other items in connection with rectifier equipment brief mention will be made of the high speed circuit breakers only. In these switches operating times down to 0·012 seconds are used, and it must be admitted that despite innovations in the way of control grids, fuses, arresters and the like the breakers remain the most effective means of protecting the rectifier from major damage, whether the potential source of trouble be short circuits, feed back, surges and even lightning disturbances on the d.c. track.

Equipment Layout.

The layout of rectifier equipment is rendered very flexible by virtue of the static nature of the plant, both the horizontal and vertical arrangements being possible. In view of the ever increasing congestion in large cities, and also modern architectural trends, the latter arrangement is becoming increasingly important and it is not without significance that the largest capacity substation in this country, the 8,000 kW Camden Town equipment of the London Passenger Transport Board, is of the vertical type shown in figs. 12 (A) and 12 (B). The arrangement shows the mounting of the high tension gear on the upper floor, the four 2,000 kW rectifiers and d.c. high-speed circuit breakers on the second floor, the control boards and link panels on the ground level and the outgoing d.c. cables in the basement. Three of the rectifiers supply power to the electric trains while the fourth is used for the tramway and trolley bus system. An interesting feature of the substation is the utilization of the frontage for shop sites.

As a result of the introduction of the pumpless type rectifier, compact arrangements are possible even where large powers may be concerned, while heavy cranes and lifting gear may be avoided. It is interesting to consider the possibilities where the three main types of rectifier are competitive and fig. 13 shows by way of example the layout of equipments for an output of 2,000 kW at 600 volts as supplied by (*a*) glass bulb ; (*b*) air-cooled pumpless steel tank, and (*c*) water cooled rectifiers respectively. An important factor in any such comparison is the overload rating of the units, and fig. 13 is based on the heavy traction overload as indicated. The areas directly occupied by the actual rectifier plants are respectively, 0·12 sq. ft. per kW for the glass bulbs and 0·078 sq. ft. per kW for the pumpless rectifiers and also for the water cooled types. The figures quoted include access space.

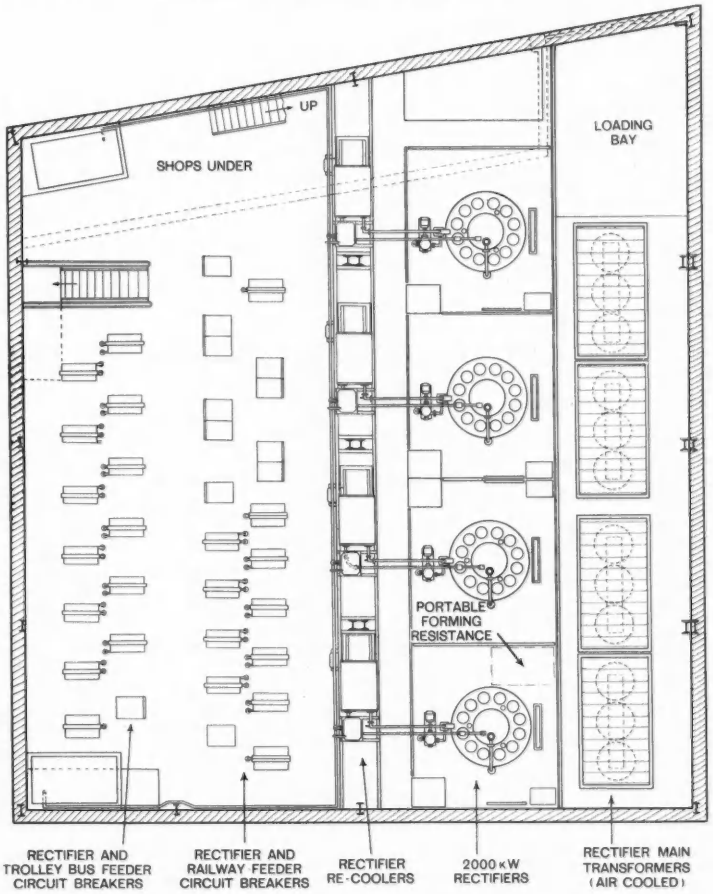


Fig. 12 (A)—Plan of rectifier floor of Camden Town Substation.

7. THE SCOPE AND PERFORMANCE OF RECTIFIER PLANT.

The power rectifier has had widespread application and there are no signs of its limits of usefulness being approached. Both the reliability and economy of rectifier plant are well established and from the performance standpoint interest lies mainly in the direction of efficiency and overload capacity. Despite the fact that rectifiers can withstand short circuit without serious damage, their thermal capacity is

comparatively low and the duration of the permissible overloading period diminishes very rapidly with increasing overload. The net result is often to the effect that where a rectifier plant of capacity adequate to deal with the brief very heavy overloads is installed, its normal duties so far as the rectifier is concerned may be relatively light. This is particularly noticeable in traction work, and more especially where rectifiers are in use in parallel; in a sense the effect can be interpreted as leading to a very conservative rating of the units for normal conditions, and the fact that it is possible to do this and still maintain a good economic performance is largely due to the flattened form of the rectifier load-efficiency characteristic.

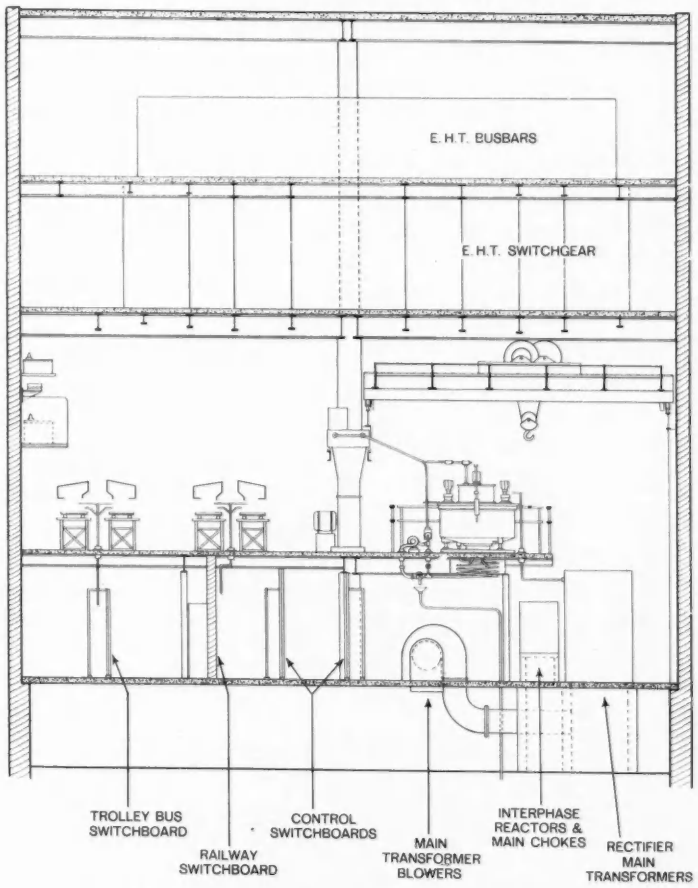


Fig. 12 (B).—Section through Camden Town Substation.

Yet another aspect of the efficiency and overload questions is that of the working voltage for the rectifier. As already mentioned, it is necessary from deionisation considerations to derate the rectifier when the working voltage is raised, on the other hand the arc drop is approximately the same and a considerable gain in efficiency usually results. The derating of the rectifier also reduces the thermal loading so that if a high voltage rectifier is designed to withstand momentary heavy overloads, it has every prospect of a good performance under standard overload conditions.

Rectifiers for Traction Purposes.

It is usual to consider rectifiers for traction work as being divided into two categories, namely, heavy traction and light traction. Under the heading heavy traction, rectifiers fulfil duties in connection with main line electrification, regenerative braking, frequency changing, electric locomotives and portable substations.

Although two 50/16⅔ frequency changing rectifier equipments of 3,600 and 4,600 kVA respectively have been installed in Germany where there are also rectifier locomotives being tried out under service conditions, it would appear that such developments will be restricted to the Continent. So far as Great Britain and the Colonies are concerned, most of the traction will be supplied at pressures of 500 volts, 1,500 volts or 3,000 volts direct current. Attention will, therefore, be directed to d.c. traction, and it may be mentioned that the increasing use of the metadyne and similar methods of motor control are bringing regeneration with its attendant inverter problems increasingly to the fore.

Some typical examples of rectifier traction work associated with British industry are the London Transport's system, the electrification of the Southern Railway, the South African Railways and the Polish State Railways. A comprehensive survey of the London Transport's electrical equipment has already recently been given before the Institution.[13] It might be mentioned, however, that a unique feature of the undertaking is the employment of each of the main types of mercury arc rectifier. These range from the 2,000 kW water cooled types down to the 250 ampere steel pumpless air cooled rectifiers,[14] and also glass bulb rectifiers for similar outputs to the latter. The water cooled rectifiers are used on the railway services and the other types on the trolley-bus and tram supplies. Operating conditions are at times severe, ranging from dense traffic in the city to single trains on outlying sections. The fact that an undertaking of this nature with its enormous peak loads is not only largely dependent upon rectifiers, but is relying on them for its extension

13 A. L. Lunn. "Equipment and Performance of Steel Tank Rectifiers." Journal I.E.E., 1936, Vol. 78, p. 123.

14 "Sealed Metalclad Mercury Arc Rectifiers," Electrical Times, 1936. Vol. 81, p. 815.

programmes, says much for the reliability and confidence placed in this type of plant.

The Southern Railway scheme[15] is noteworthy as representing the beginning of an era long foreshadowed in connection with the British main line railways. The rectifier equipment involved amounts to 250,000 kW corresponding to 100—2,500 kW equipments. The rectifier equipments are installed in single unit substations and at certain points of the system operate in parallel with compound rotary converter substations. Each equipment consists of a steel tank rectifier with main transformer and switch gear controlling equipment which controls auxiliary plant and is designed for the following typical d.c. ratings for traction work:

2,500 kW continuously at 600 volts.
3,000 kW for fifteen minutes.
4,000 kW for five minutes.
6,000 kW for thirty seconds.
8,000 kW momentarily.

The South African Railway electrification[16] represents 320 miles of main line working at 3,000 volts d.c. Regenerative braking necessitated the installation of inverter equipment and to overcome switching limitations, use of permanently reverse connected rectifiers to pass the regenerated current. In common with similar schemes the actual total amount of returned energy to the a.c. system will, after allowing for the portion absorbed amongst the load of other trains, only amount to a small percentage and even if returned at a low power factor should not affect the a.c. system. The important feature is that the full retarding force shall be instantly available when required, special tests with two 1,000 ton trains and subsequent operating experience has confirmed this.

Another feature is the use of high speed relays to suppress the arc by applying a negative voltage to all grids in the case of a backfire or internal short circuits on the rectifier. Track short circuits are dealt with by means of external feeder breakers. The forward loads represent a continuous rating of 1,667 kW on each unit, the corresponding overloads being as shown herewith.

Direct.	Inverted.	
50%	25%	2 hours
110%	110%	30 minutes
200%	175%	1 minute
260%	200%	momentarily

The complete equipment is also rated with a particular load curve. It is interesting to note that in connection with the actual working, a loading of almost three times full load has been carried for 11 minutes.

So far as the grid control equipment is involved the rectifiers are of normal 3,000 volt construction fitted with double control grids and polyphase

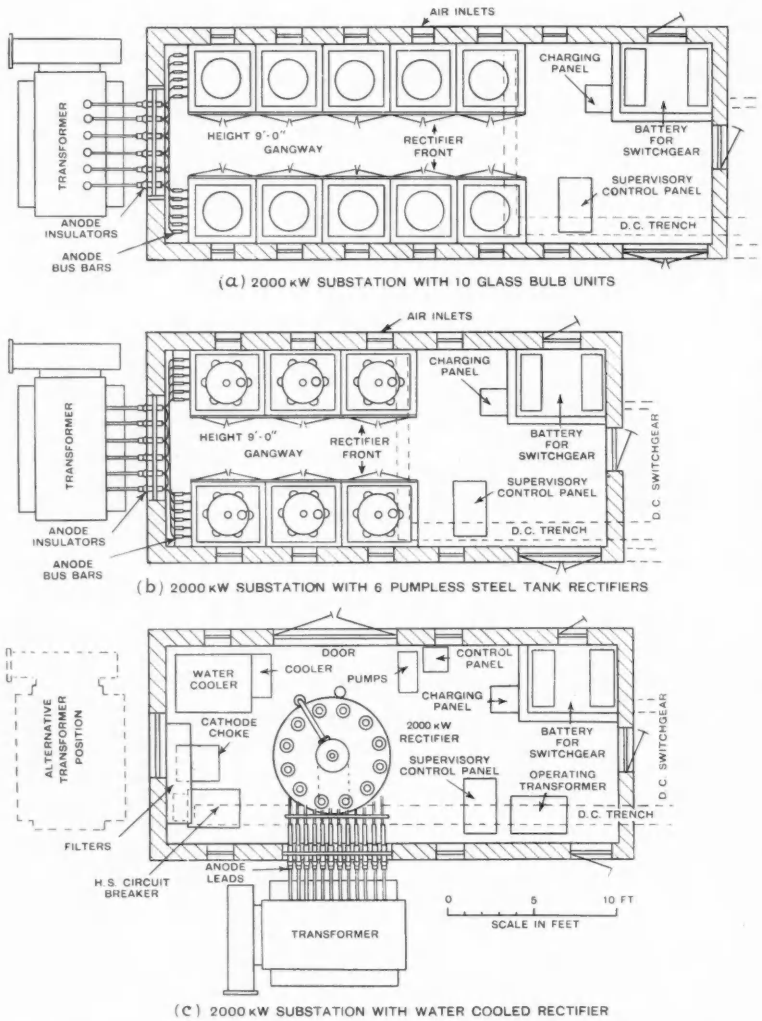


Fig. 13.—Proposed arrangements for 2000 kW, 600 volt traction substation. Overloads—50% for one hour, 200% for fifteen seconds.
(a) Substation with ten glass bulb units.
(b) Substation with six pumpless steel tank rectifiers.
(c) Substation with water-cooled rectifier.

15 The Railway Gazette. (Electric Railway Traction Supplement), June, 1937.

16 "The Engineer," 1936, Vol. 162, p. 66.

excitation. Using the torque-motor actuated control for the peaky wave ignition transformer, the response was more than sufficiently rapid for railway service. The use of resonant shunts has effectively reduced the telephone interference factor of the voltage ripple to 0·5 per cent despite the use of grid control and 6 phase transformer connections. The overall efficiency at full load rectifying was 96 per cent and at full load inverting 94 per cent.

The Polish State Railways[17] are supplied from thirteen 3,300 volt rectifiers arranged in six substations and aggregating some 35,000 kVA. The combined capacity of the station supply in the rectifier is 143,000 kVA and the rectifier load thus amounts to 24·5 per cent. To meet low ambient temperatures small heaters are fitted to switchgear control gear. The power transformers are also equipped with a tertiary six phase star connected winding for baking out the rectifiers at low voltage. The overload figures are 25 per cent for fifteen minutes and 200 per cent momentarily.

The guaranteed overall efficiencies are:

Load	5/4	4/4	3/4	2/4	1/4
Effcy % :	96·07	96·6	96·82	96·72	95·57

Protection on the d.c. side consists of reverse high speed breakers between cathode and busbars and forward high speed breakers between busbars and the track, while to minimize interference the smoothing reduces ripple to less than 1½ per cent of the normal d.c. voltage. Three substations are manually controlled, the remainder being remote controlled.

Despite the fact that it is a comparative newcomer to the rectifier group, the pumpless steel tank rectifier has met with considerable success. Some ten thousands of kilowatts of this type are in service. The parallel arrangement of the units for larger powers enables a high efficiency to be maintained together with overload performances comparable with water cooled rectifiers. Substations of a capacity of 1,000 kW have been equipped with these types.

A typical example is that of a 600 kW, 500 volt equipment supplied to a Glasgow printing works. The two 600 ampere pumpless steel rectifiers are each housed in a cubicle containing the cooling fan and the usual auxiliaries. The d.c. supply is on the three wire system, a neutral point for the third wire being efficiently and effectively obtained by means of a rotary balancer, The usual standard overloads and efficiencies were obtained without difficulty.

Yet another example is the 500 kW, 600 volt unit supplied for Perth, Australia. This is one of the first grid controlled pumpless steel tank rectifiers and is arranged to give constant voltage for all loads up to full load. The control potentials are applied to the grids by the synchronous distributor method, suitable voltage responsive relays being provided for actuating the brush rocking gear. The control gear is neatly housed in a separate cubicle from the rectifiers.

Glass bulb equipment represents a considerable aggregate of installed plant and covers a wide range of outputs from large 6,500 kW traction substations down to small units for cinema projectors. They are too numerous to be discussed in detail, but the rectifiers associated with the Liverpool Southport and Manchester Bury lines respectively might be quoted as typical examples. The former is a 600 volt system with 1,000 ampere rectifier banks, the latter a 1,200 volt scheme with substation capacities of 3,000 amperes. In each case the overloads are 25 per cent for two hours, twice full load for ten minutes and three times full load peaks momentarily. The respective efficiencies are of the order of 94 per cent and 96 per cent.

Turning to the high voltage field, a 100 kV experiment in d.c. transmission has been tried out in Switzerland, and also the H.T., D.C. constant current equipment at Schenectady, U.S.A. must be mentioned.

Mercury arc rectifiers for radio broadcasting are also well established, amongst the latest achievements being the new Empire Broadcasting Station at Daventry. The entire main high tension d.c. supply is furnished by five rectifiers of the steel tank type, rated at 400 kW for either 12,000/14,000 volts or 19,000/22,000 volts. The normal voltage control to these equipments is given by induction regulators, but the rectifiers are also able to give control of the voltage from zero to 22,000 volts by means of grids. New type high speed relays are incorporated to suppress the rectifier arc in the event of flashover in the transmitter valves. Incidentally these rectifiers withstood 30,000 volts, 400 kW for fifteen minutes.

Mention might be made in passing of the application of rectifiers to film studios, the characteristic type of load being long intervals of light load followed by short heavy load periods of heavy loading during the actual filming. A typical equipment supplied to the Amalgamated Studios Ltd. at Elstree consisted of 500 kW, 240 volts, steel tank rectifiers. Utilising the heavy overload capacity in combination with the three wire working, it will be possible to supply brief lighting loads for 16,000 amperes. Special smoothing equipment is provided to ensure the smooth and silent operation of the arc lights.

Two types of rectifier, the pumpless air-cooled steel tank type and ignitron are being applied to mining work below ground. The former is a 250 kW unit to be supplied to one of the Rand Mines and the latter is being used in America to give a 225 volt, 300 kW supply for haulage and machinery operation. This ignitron equipment was arranged for full automatic control and voltage compensation for both

17 "Engineering," 1936, Vol. 141, p. 201.

line and transformer reactance. The compensation was arranged by combining the effects of load and line voltage, and applying this to the impulsing transformer neutral. Beyond full load use was made of the normal shunt characteristic. The overload ratings were 50 per cent for two hours and 200 per cent for one minute. In six months' service only one arc-back has been recorded.

All types of mercury vapour rectifiers are finding application in the chemical industry, large steel tank water-cooled sets up to 8,000 kW being used. A feature of this class of service is the low voltage starting required on some of the electrolytic baths and the possibility of feed back currents of over 10,000 amperes in the event of a rectifier arc-back. As a result both grid control and arc suppression are of importance.

Similar heavy duty rectifiers are required in connection with rolling mill work where in some cases circuits to give the usual Ward-Leonard operating characteristics are used.

Other applications of rectifiers are to electric locomotives, portable substations, high power tests, hotel loads, printing works, large stores, docks, etc. The foregoing by no means exhausts the list of applications, but is sufficient to indicate the extremely wide scope of application of rectifiers.

8. CONCLUSIONS.

There is little doubt that the sustained importance of direct current electrical engineering has been largely due to the progress of the rectifier. This device has enabled the benefits of the flexible control of direct current plant to be combined with the economics of alternating current distribution. The rectifier has also had a far-reaching influence on transport, and the progress of main line electrification and trolley bus systems throughout the world, is of significance in this respect.

Rectifiers have now been in course of development for over a third of a century and whilst there may be comparatively little further change in the essential features, there is no reason to suppose that finality in design has been reached. One of the difficulties in rectifier development has been the lack of economical means of carrying out full load tests at large powers; it is of interest to note that a rectifier testing station has recently been built at the Witton Engineering Works and is capable of testing rectifiers up to 6,000 kW at voltages up to 4,000 volts, while equivalent tests corresponding to loadings at 12,000 kW are possible.

A study of the rectifiers themselves suggests that air cooling even for larger sizes will eventually be adopted and that the vacuum pumps will inevitably disappear as a unit feature of each rectifier. So far, it would be true to say that grid control as a means of voltage regulation has proved less popular than was thought probable a few years ago. Some of the theoretical possibilities have not materialised and there have also been limiting economic factors to other forms of controlled operation.

With high voltages the demand has proved smaller than anticipated, radio broadcasting, rather than direct current transmission, would appear to be the limits of requirements. So long as the transmitting valve policy remains as at present there will be little demand for rectifiers above 20 kV. The future of the lower voltage working is bound up with the question of arc drop and in this connection the use of single cylinders per anode and also the jet wave rectifier appear to have brought us to a lower limit than was previously economically possible.

There is little doubt that the great outlet for power rectifiers will remain the 500 to 3,000 volt range, where not only has their confidence been established, but also where their application has resulted in considerable savings to the community as a whole.

The Concentration of Minerals by Flotation.

PART II.

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SURFACE-ENERGY OF SOLIDS.

ALTHOUGH the molecules of a solid are relatively immobile compared with those of a liquid, its surface possesses a definite amount of potential energy due to unbalanced attractional forces similar to those exhibited by a liquid. Whether or not the solid possesses surface-tension is not known as no means have been found of making the necessary measurements, but the forces acting outside the boundary may be considered from a purely conventional point of view as divisible into two components :—

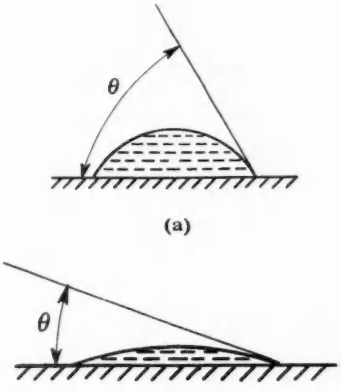


Fig. 1.

(1) An attractional force acting vertically to the surface ;
(2) A tension exerted parallel with it.

Thus, if a drop of water be placed on a solid, the surface-energy of both substances is partly expended across the interface between them as a mutual attractional reaction (*adhesion*). It is doubtful if adhesion is ever so complete as to absorb all the energy of the system, and so a certain amount remains as *interfacial energy*. It represents the surplus molecular attractions not mutually engaged in producing adhesion between water and solid across the interface, and it may be conventionally regarded as exerting a tension (*interfacial tension*) which holds the water back from any further invasion of the solid surface.

The interfacial energy, and therefore the assumed interfacial tension, is constant for a given solid-liquid interface. Consequently, a drop of water or other liquid should assume a definite shape and cover a definite area when placed on a particular solid-surface, and on another type of surface a drop of the same volume should assume a different but equally definite area. This is actually found to be the case. The shape of a drop of water placed on the surface of a sulphide mineral, which has been treated by one of the methods described later so as to render it floatable, is indicated in fig. 1a, whereas on the surface of a rock-forming mineral such as quartz, its shape is like that shown in fig. 1b. It has been determined experimentally that the *contact-angle*, θ, made by the water at every point of contact with the dry solid-surface varies with the nature of the surface but is constant for a given type of surface.

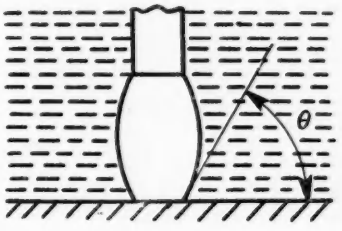


Fig. 2.

The value of θ is thus a measure of the degree to which the liquid tends to wet the surface of the solid ; applied to flotation, it is a measure of the "*floatability*" of the mineral. It should be noted that the measurement of contact-angles is made by bringing a captive air-bubble in contact with the solid-surface under water as shown in fig. 2 ; the contact-angle is indicated as before by θ. This is more accurate than measuring the angle made by a drop of water placed on the surface of the solid. The measurement of contact-angles is employed in research laboratories for investigating the principles of flotation, but it has not so far been used as a means of control in commercial installations.

The relation between the contact-angle and floatability can be understood by considering the effect of floating or trying to float a small piece of mineral on a water-surface. The way in which a particle of floatable mineral clings to the surface is shown in fig. 3. The illustration can be assumed to represent a small section of an air-bubble in water, and as such it shows how a particle of floatable mineral clings to a bubble in a floatation machine. It will be seen that the surface-tension of the water, acting in the direction indicated by T at all points on the line of contact where the edge of the water meets the surface of the mineral, exerts a pull which tends to hold the particle in equilibrium at the surface of the water, the strength of the pull depending on the inclination of T (the contact-angle) and

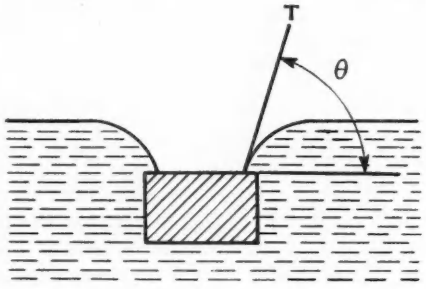


Fig. 3.

the length of the line of contact. For the mineral to float as in fig. 3, the total force holding it in place must be strong enough to keep it there against all the forces tending to dislodge it, such as collisions with particles of ore or with other bubbles, as well as against the pull of gravity. The effect of gravity is appreciable when the mineral approaches the critical upper limit of size (50 mesh), but it diminishes rapidly with decrease in size.

If the contact-angle could be slowly reduced by some means; that is, if the adhesion between mineral and water were slowly increased, the water would gradually invade the dry surface of the solid, and the effective pull of T, acting at a lower inclination along a shortened line of contact, would decrease, until some point were reached at which it would be unable to maintain the particle in stable equilibrium. The slightest disturbing force would then dislodge it from contact with the bubble-surface; that is, from the point of view of flotation the mineral would have been rendered unfloatable.

The actual value of the contact-angle, which determines floatability, is a function of the difference in surface-energy between the "unwetted" surface of the solid (the *air-solid interface*) and that part which is in contact with the water (the *water-solid interface*). Thus a high degree of adhesion between solid and liquid implies a strong tendency for the liquid to wet and spread over the surface of the solid (small contact-angle and low floatability) with a large reduction in surface-energy, *i.e.*, a large difference between the interfacial energy of the air-solid and water-solid interfaces. Conversely, a low degree of adhesion implies a tendency for the solid to repel the liquid from its surface (large contact-angle and great floatability) with little reduction in surface-energy, *i.e.*, a small difference between the interfacial energy of the air-solid and water-solid interfaces. The art of flotation consists of regulating these differences in interfacial energy so as to render the valuable minerals water-repellent, *i.e.*, floatable, and the gangue material comparatively unfloatable. The flotation process owes its existence to the fact that many minerals of the base metals can be rendered water-repellent by comparatively simple means without affecting the surfaces of the rock-forming minerals. The latter tend to enter the liquid phase and become wetted, and are thus naturally unfloatable.

Collecting Reagents.

The means by which the valuable minerals are rendered floatable has changed considerably in recent years. In the early days of flotation the manner of achieving this object consisted almost exclusively in filming the surface of the mineral with a layer of some heavy ***collecting oil*** or ***collector***, such as crude fuel oil, wood tar creosote, or coal tar creosote, the main constituents of which are too insoluble to possess frothing properties. The action of these oil-filming reagents depends on the fact that they tend to spread over mineral surfaces that have a metallic lustre, such as is possessed by most of the sulphide minerals of the base metals. Placed on the surface of a rock-forming mineral or on one with a resinous lustre or earthy structure, they generally exhibit no tendency to spread. The result is much as illustrated in fig. 1 but with the positions reversed as compared with water; that is fig. 1a represents a drop of oil on a piece of rock, while fig. 1b represents the same drop on the surface of a sulphide mineral. What happens is that the oil is adsorbed at the surface of the sulphide mineral with considerable reduction in surface-energy at the interface and so tends to spread, whereas it has little tendency towards adsorption at the surface of a rock-forming mineral. By the method described in the next paragraph the particles of sulphide mineral in an ore pulp can be coated with a film of oil, while the gangue material remains more or less untouched. The water-repellent nature of an oily or greasy surface is well known. Water spilt on an oily work-bench will separate into drops and patches and will not spread over the surface. In the same way a drop of water placed on a piece of oiled mineral will

heap itself up into a more spherical form than if it were placed on a clean unoiled surface of the same mineral; that is, it will exhibit a larger contact-angle. In other words, filming the mineral with oil renders it water-repellent to the extent that it tends to leave the liquid phase and adhere to the surface of any bubble with which it comes in contact in the flotation cell.

The oil-filming process—it is almost obsolete now—was effected in practice by agitating the finely ground ore-pulp with a considerable degree of violence for several minutes with the necessary amount of heavy oil, usually ½-1 lb. of oil per ton of ore treated. The operation was generally carried out in a square cell with a cruciform impeller rotating in the bottom. The pulp entered the cell continuously at one side near the bottom and passed out over an adjustable discharge-weir at the opposite side. The collecting oil was fed at the required rate into the cell, and was emulsified there by the intensity of the agitation and at the same time distributed evenly throughout the pulp. The main constituents of the oil, being insoluble, or nearly so, and strongly water-repellent, were thrust out of the liquid phase and concentrated at the air-water and water-solid interfaces in the form, probably, of minute drops. At every water-sulphide-mineral interface adsorption of the oil took place as already described. Thus the valuable minerals became coated (whether partially or completely is not known) with a film of oil which made their surfaces water-repellent and the particles correspondingly floatable. It is conjectured that an oil-film so formed is of appreciable thickness rather than of molecular dimensions. Substantially less adsorption of oil took place at the surface of the rock-forming minerals, which therefore remained comparatively unfloatable. The ore-pulp, thus prepared, passed from the agitation cell direct to a flotation machine where concentration of the floatable minerals in a froth was carried out by the normal method, which has already been described.

The oil-filming method of flotation has been superseded in recent years by the use of what are termed *chemical promoting reagents*. The characteristic of the former process was the toughness of the froth, which was presumably due to the presence on the minerals and round the bubbles of adsorbed layers of a comparatively large quantity of collecting oil, *i.e.*, ½-1 lb. of oil per ton of ore as compared with 0·05-0·15 lb. of chemical promoter per ton in modern practice. Colliding mineral-laden bubbles thus tended to stick together through coalescence of

Fig. 4.—Copper flotation and smelting plant of the Indian Copper Corporation, Bengal, India; designed and erected by the Fraser & Chalmers Engineering Works of the G.E.C.

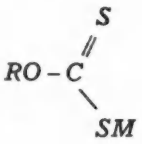
these relatively thick films, and the froth that formed on the top of the flotation machine was tough in consequence and did not readily break down. The only use of collecting oils at the present day is to toughen a fragile froth, and 0·1-0·3 lb. of oil per ton of ore is generally sufficient for the purpose.

The term *collecting oil* or *collector* was given to these reagents because of their property of collecting the minerals in an agglomerated and sometimes sticky mass of bubbles. The so-called *chemical promoting reagents* or *promoters* employed in modern practice change the surfaces of the minerals to be floated to a condition which is in effect oily, *i.e.*, water-repellent, but the coatings formed are more in the nature of chemical films of mono-molecular dimensions, and on account of their minute thickness there is little chance of the films coalescing when two mineral-laden bubbles collide. These reagents, therefore, are termed *promoters*, because their action is to promote the floatability of the wanted minerals without collecting them into an agglomerated mass of bubbles. In fact, one characteristic of the chemical filming process, when properly carried out, is the ease with which the froth breaks down to a pulp of mineral and water as it comes away from the flotation machine.

Promoting Reagents.

The *promoting reagents* or *promoters* employed in modern flotation practice are mainly *xanthates* and *aerofloats* or their derivatives.

A *xanthate* is a di-thio-carbonate with a general formula :—

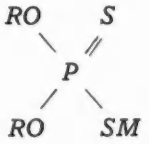


in which *RO* is an organic radicle and *M* is a metal. As far as flotation reagents are concerned, *RO* is always a radicle of one of the aliphatic alcohols, usually ethyl, butyl, or amyl alcohol, and the metal *M* is potassium or sodium, generally the former, since sodium xanthates are on the whole less stable.

"Aerofloat" is the trade name given to a corrosive liquid formed by the action of phosphorus penta-sulphide on cresylic acid under heat and pressure. It contains a small proportion of free cresylic acid, but the active promoting compound is mainly di-cresyl-di-thio-phosphoric acid, which can be represented by the general formula :—

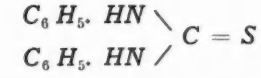
RO representing the cresyl radicle. Due to the presence of free cresylic acid, which is a frother aerofloat has both frothing and promoting properties.

The hydrogen in the above formula for aerofloat can be replaced by an alkali metal, in which case a di-thio-phosphate is formed with the general formula :—

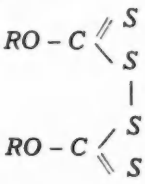


It is not quite such a strong promoter as aerofloat itself, but it has the property of promoting without frothing, which is sometimes an advantage when the pulp already contains enough frothing reagent. Other di-thio-phosphates are made by replacing one or both of the cresyl groups with a phenyl radicle.

In addition to the promoters mentioned above, all of which possess a group of the type , there are others which have single or double sulphur groups. Thus di-phenyl-thio-urea, or *thiocarbanilide*, has a single sulphur group :—



Di-xanthogen, a derivative of the xanthates, has two sulphur groups :—



RO being the radicle of an aliphatic alcohol.

It will be seen that all the promoters mentioned above contain a group of the type or $= S$ connected through an atom of carbon or phosphorus with a group of hydrocarbons. It has already been explained in the section on frothing reagents how, if a polar-nonpolar compound with a hydroxyl (*OH*) group is immersed in water, the polar *OH* part tries to pull the nonpolar hydrocarbon tail into the water-phase. The promoting reagents are also polar-nonpolar compounds, though with a more complicated structure than the alcohol frothers, and the polar $= S$ or groups, or in the case of aerofloat the group, has the same ten-

dency as the *OH* group to pull the hydrocarbon tail into the water-phase. The chemical promoters with one or two exceptions are in fact readily soluble in water and ionize in it in varying degrees.

The polar group of the promoter, or perhaps the double-bonded sulphur atom only (=*S*), has the property not possessed by an *OH* group of attaching itself to the surfaces of the sulphide minerals of most of the heavy metals and to some native metals; it has been described as the mineral hook of the promoting reagents. The way in which the attachment is effected has not been definitely established. One school of thought[3] maintains that it is chemical in its nature; that the surface of the sulphide mineral takes up oxygen from the aerated pulp to form a sulphate or some more or less soluble salt, which reacts with the xanthate or other promoter by *metathesis* (double decomposition), an insoluble xanthate being deposited, thus:—

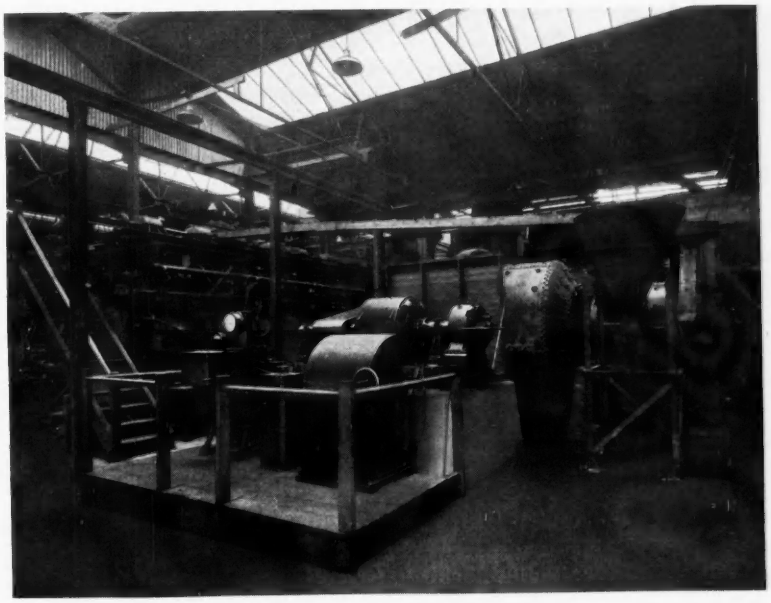


Fig. 5.—Fraser & Chalmers concentrating plant at a tin mine in Cornwall, showing the concentrate regrinding and flotation section.

Alkali-metal xanthate + heavy-metal sulphate = alkali-metal sulphate + heavy-metal xanthate.

Oxidation of the mineral as postulated must first occur if the chemical theory is correct, because the mineral surface, being less soluble in water than the xanthate with which it eventually becomes filmed, must be converted to something more soluble than the xanthate in order to make it possible for the subsequent double decomposition to take place.

How the heavy-metal sulphate, which may be very soluble in water (*e.g.*, copper sulphate), is held at the surface of the mineral while the reaction takes place and the insoluble heavy-metal xanthate is deposited on the mineral is not very clear, but the exponents of the theory claim that such a reaction does take place whenever a mineral is filmed by one of the chemical promoters.

Other experimenters[4] state that the chemical theory cannot be considered as proved, because insoluble heavy-metal salts of some of the promoters have never been isolated as definite compounds; that the film is formed on the mineral in some cases by simple adsorption without chemical reaction, the $\diagup\!\!\!\!\diagup S$ radical being orientated towards the min-$\diagdown SM$ eral; that exchange adsorption between the surface of a mineral and the promoter may occur in other cases and could take place without preliminary oxidation of the surface, and that this is a more feasible explanation of the formation of a film on the surface of a mineral than double decomposition.

Whatever the process by which the mineral is filmed, there is no doubt that the promoter forms a mono-molecular layer over its surface, the mineral hook being attached to or oriented towards the surface of the mineral and the hydrocarbon chain being oriented away from it. In effect, the particles of mineral become covered with a film of strongly water-repellent hydrocarbon groups analogous to the oil-film of the earlier process. The so-called chemical film, however, exhibits a higher contact-angle than an oil-film. The chemically filmed particles are therefore more floatable and for that reason are more readily caught by bubbles rising through the pulp in a flotation machine. It follows that they can be collected with less bubbles than are required in the oil-filming process, and there is consequently less tendency for particles of gangue to be trapped between bubbles; there is also less tendency for the bubbles themselves to stick together. In other words, the chemical filming process yields a higher recovery of the valuable minerals and a cleaner froth.

Since the hydrocarbon group forms the outer skin of a particle of filmed mineral, one would expect the contact-angle to be the same for a particular promoter whatever the type of the mineral filmed. Also, one would expect the contact-angle to increase with the length of the hydrocarbon chain, since a

3. A. F. Taggart, T. C. Taylor, and A. F. Knoll: "Chemical Reactions in Flotation." Transactions, American Institute of Mining and Metallurgical Engineers (1930), "Milling Methods."
A. F. Taggart, G. R. M. del Giudice, and O. A. Ziehl: "The Case for the Chemical Theory of Flotation." Transactions, American Institute of Mining and Metallurgical Engineers (1934), Rocky Mountain Fund Volume on "Milling Methods."

4. I. W. Wark and A. B. Cox: "Principles of Flotation, V." Transactions, American Institute of Mining and Metallurgical Engineers (1936), Tech. Pub. No. 732.

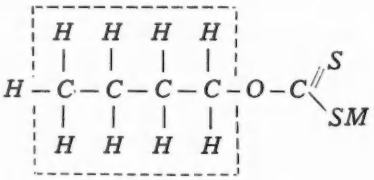
long chain is more water-repellent than a short one. A series of investigations by I. W. Wark and A. B. Cox[5] on the action of xanthates has proved this to be true. Some of their work is summarized in the accompanying table which shows the angle of contact exhibited by various xanthates; the angle was found to be constant for a given xanthate whatever the mineral on which the film was deposited.

CONTACT-ANGLES GIVEN BY XANTHATE PROMOTERS.

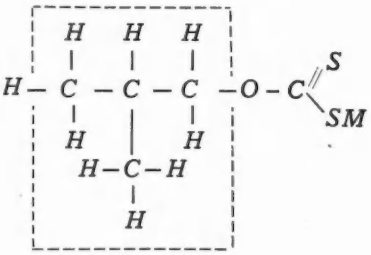
Type of Xanthate.	Formula.	Contact-Angle degrees.
Methyl	$CH_3.OC.SSM$	50
Ethyl	$CH_3.CH_2.OC.SSM$	60
n-Propyl	$CH_3.(CH_2)_2.OC.SSM$	68
n-Butyl	$CH_3.(CH_2)_3.OC.SSM$	74
iso-Butyl	$CH_3.(CH_2)_3.OC.SSM$	78
iso-Amyl	$CH_3.(CH_2)_4.OC.SSM$	86
Cetyl	$CH_3.(CH_2)_{15}.OC.SSM$	96

It should be noted that the normal and iso-butyl xanthates give slightly different contact-angles. The difference in the structure of their (CH_2) groups, as shown below, probably accounts for this :—

n-Butyl Xanthate

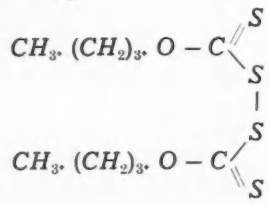


iso-Butyl Xanthate

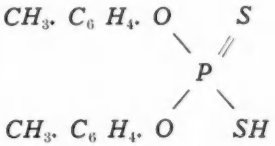


The table shows clearly that a xanthate with a long chain exhibits a higher contact-angle, and is therefore a stronger promoter than one lower down the scale.

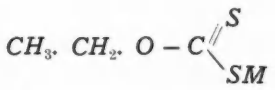
Similarly, it has been found that promoters such as butyl di-xanthogen :—



and aerofloat :—



with their double tails are more powerful than one with a short single chain, such, for instance, as ethyl xanthate :—



One would expect a long or double-chain promoter to be employed, therefore, in preference to one with a short chain on account of its greater floating power. For most ores, however, an ethyl xanthate is quite strong enough to bring up the mineral, and, as it is about half the price of the others, its use is generally preferred. Even when a stronger promoter is found to yield a better recovery of the valuable minerals, the bulk of them can often be floated with ethyl xanthate, the remainder being brought up subsequently with a correspondingly small proportion of the more expensive reagent. The quantity of promoter or mixture of promoters required in normal flotation practice varies from 0·05 to 0·15 lb. per ton of ore treated.

It is beyond the scope of this article to discuss the suitability of the various promoters for different minerals, especially as no hard and fast rules can be laid down. When the problem arises of finding out the best combination of reagents for the flotation of a new ore, contact-angle measurements and theoretical consideration derived from pure research may afford some guide, but small-scale tests in a laboratory flotation machine, based on practical experience with similar ores and minerals, comprise the normal method of getting the required information.

DEPRESSING, ACTIVATING AND OTHER CONDITIONING REAGENTS.

Depressing Reagents.

It may happen that two or more classes of floatable minerals are present in an ore but only one is required in the concentrate. The operation of bringing up the wanted mineral without the other is termed selective flotation. Occasionally a promoter can be found which will affect only the wanted mineral, but it is generally necessary to use a special *depressing reagent*, or *depressor*, to prevent the unwanted mineral from floating. For instance, when the sulphide minerals of copper or zinc occur in combination with pyrite (FeS_2), if no depressor

5. I. W. WARK and A. B. COX : "Principles of Flotation, I." Transactions, American Institute of Mining and Metallurgical Engineers (1934), Rocky Mountain Fund Volume on "Milling Methods."

is used for flotation, a large proportion of the pyrite will enter the froth, whatever promoter be employed to float the copper or zinc mineral. But if lime be added to the circuit in sufficient quantity to raise the alkalinity of the pulp above a certain critical value, which expressed in terms of its *hydrogen-ion concentration* (*pH*), is usually about 10 but varies with different ores, the pyrite will be depressed to the extent that it cannot be floated by the addition of a normal quantity of any promoting reagent, though the flotation of the wanted copper or zinc mineral will not be affected. A *pH* of 7·0 represents the neutral point, values below that figure being acid and above it alkaline.

G. R. M. del Giudice[6] explains the action by stating that depressing reagents "apparently all function by reacting with the surfaces of minerals to form thereon salts which are less soluble than the salts that would be formed by the reaction between the soluble collectors and the surfaces of the same minerals." In other words, the double decomposition reaction, which, it is assumed, would normally occur between the mineral-surface and the promoter with the formation of an insoluble water-repellent film, is prevented from taking place by the previous formation through the action of lime of a more insoluble, though less water-repellent, film. It can scarcely be considered as proved, however, that an actual double decomposition reaction occurs between the lime and the pyrite-surface, and the coating which causes the depression of the mineral may be due to simple or exchange adsorption. But, whatever the explanation, lime is the most effective depressor for pyrite when present in the pulp above a certain critical concentration.

Another common case is that of an ore containing lead and zinc sulphides, such as galena, *PbS*, sphalerite, which is more or less pure *ZnS*, and or marmatite, which is zinc sulphide containing up to 15 per cent of iron. Zinc minerals cannot normally be floated by the addition of a promoting reagent that will bring up the galena, but a very small amount of a soluble copper salt in the pulp will activate them by depositing a film of copper sulphide on their surfaces; this appears to be a true double-decomposition reaction. Any promoting reagent that is then added to float the galena will also bring up the coated zinc minerals, a mixed concentrate being produced which has an undesirably low market value on account of the difficulty and expense of smelting it. Most lead-zinc ores contain a small proportion of copper mineral which generally reacts as described above; presumably some of it oxidizes during the grinding operation and subsequently goes into solution, causing the zinc sulphides to float with the galena as described. The zinc minerals can be depressed, however, by the addition of a certain critical amount of a soluble cyanide, usually the sodium salt, the amount used being normally 0·1 to 0·5 lb. per ton of ore. The generally accepted explanation is that, when soluble copper salts are present in the pulp, the copper-ion concentration must be above a (very small) critical value in order to react with zinc sulphide, and that the cyanide which is added converts the copper in solution, or actually on the sphalerite or marmatite, to a soluble cupri-cyanide, thus locking up most of the copper in a complex ion and reducing the free copper-ion concentration below the value at which it can activate the zinc sulphides.

The use of a mixture of zinc sulphate and sodium cyanide is often more effective than cyanide alone in depressing zinc sulphides; the reason for its action has not been established. Zinc sulphate alone and also sodium sulphite exert a slight depressing action on sphalerite, and both are occasionally employed. Sodium cyanide is also used in the place of, or in conjunction with, lime to depress pyrite.

Activating Reagents.

An *activating reagent*, or *activator*, has an effect exactly opposite to that of a depressor; it reacts with the surface of a depressed or unfloatable mineral in such a way as to render it floatable in the presence of a suitable promoter. The outstanding example is copper sulphate, which is invariably employed to activate the zinc minerals in the second or zinc-flotation stage of the concentration of a lead-zinc ore. The first or lead-flotation stage, in which the zinc sulphides are depressed by sodium cyanide, or other depressor, has been described. In the second stage the zinc minerals are activated by means of an excess of copper sulphate; sufficient must be used, generally 0·5 to 1 lb. per ton of ore, to neutralize the depressing effect of any cyanide remaining in the pulp in addition to the amount needed to raise the copper-ion concentration to the required critical value, as already explained. A contact period, which is normally from 5 to 20 minutes depending on the nature of the ore, is required before activation is complete, after which the coated zinc mineral can be floated by means a a xanthate or di-thio-phosphate promoter. Copper sulphate also activates pyrrhotite (Fe_7S_8) and to some extent also pyrite (FeS_2).

The only other common activator is sodium sulphide. It is employed in the flotation of oxidized lead minerals, chiefly cerussite ($PbCO_3$), which is unfloatable in its natural state. It is generally added to the pulp in a conditioning tank ahead of the flotation machine in sufficient quantity, usually 1 to 5 lbs. per ton of ore, to form a coating of *PbS* on the surface of the mineral. A contact time of 5 to 20 minutes may be needed before the mineral is

6. G. R. M. Del Giudice: "The Function of Depressors and Protective Agents in Conditioning for Flotation." Engineering and Mining Journal, Aug. 1934, p. 350.

completely coated, after which it can be brought up in the flotation machine with any ordinary promoter. Sodium sulphide is also employed to activate galena which has been superficially oxidized. In this case the sulphide film may often be formed in a comparatively short time, one minute or less, and the reagent can thus be introduced into the flotation machine without the necessity for a conditioning tank.

Other Conditioning Reagents.

It is generally found that a particular promoter reacts with maximum effect when the *hydrogen-ion concentration* (*pH*) of the pulp is at a definite value or at least within a definite range. Thus, with many minerals aerofloat (di-cresyl-di-thio-phosphoric acid) works best at a *pH* between 7·0 and 7·5, whereas to obtain similar flotation with a xanthate a more alkaline circuit is likely to be required with a *pH*, perhaps of 8·0 to 8·5. As already stated, a *pH* of 7·0 represents the neutral point, values below that figure being acid and above it alkaline. When the best *pH* value for the flotation of an ore has been determined, whether by laboratory experiments or in the plant itself, the pulp is maintained at that point by the addition of a *pH regulator, i.e.,* lime or soda ash (Na_2CO_3) if the *pH* is too low, or sulphuric acid if it is too high (a very infrequent occurrence). Lime is used, when possible, to raise the *pH* of a pulp, being somewhat cheaper than soda ash, but the latter reagent must always be substituted when the ore contains wanted minerals on which lime is likely to exert a depressing effect.

Apart from their functions as *pH* regulators, lime and soda ash are often required to remove undesirable salts in solution in the pulp. Thus, ferrous and ferric sulphates are formed during the grinding of most pyritic ores and may exert a very harmful effect on flotation unless they are precipitated by one of the above reagents. Interference may also be caused by hard water containing an excessive amount of calcium and magnesium sulphates. The addition of soda ash will remove these salts by converting them to the comparatively insoluble calcium and magnesium carbonates.

The only other chemicals used in flotation are dispersing reagents, which are necessary to prevent particles of *gangue slime* from coating the floatable minerals and rendering them unfloatable.

The term *slime* needs some definition. It is usually applied to particles of ground ore which are so small that they remain in suspension for an appreciable period, say for 5 minutes, when a dilute pulp of the ore in water is allowed to settle. In this sense, which is the most generally accepted one, all particles below about 30 microns (0·03 mm.) in size would be classed as slime. Unfortunately, the word is often loosely applied to any ore that is finely ground, and it is a common occurrence to hear it used to describe a product that is as coarse as 200 mesh (0·06 mm.); in some operations ore that is below 100 mesh (0·14 mm.) is referred to as slime.

As regards slime coatings, it has been established by microscopic methods that in certain conditions slime-particles of many rock-forming minerals will cover the surfaces of metallic minerals so completely as to prevent their attachment to bubbles in a flotation machine. It would appear that the metallic minerals affected are converted, in effect, into pieces of gangue, though this must be regarded as a very incomplete description of what actually happens. The method of attachment has not been established, and investigators still differ in their opinions as to the nature of the reaction that takes place. It is not a difficult matter to remove the coating or prevent it from forming. The addition of 0·5—1 lb. of water glass (sodium silicate) per ton of ore usually disperses the particles of gangue-slime so that they remain in suspension in the water. Water-glass has a wide application as a dispersing reagent and is especially useful if the gangue-material is quartz. Sodium meta-phosphate is sometimes employed in the flotation of ores containing calcite ($CaCO_3$), while starch in small amounts (0·1—0·2 lb. per ton of ore) is often effective when the gangue consists of clayey material such as talc or kaolin.

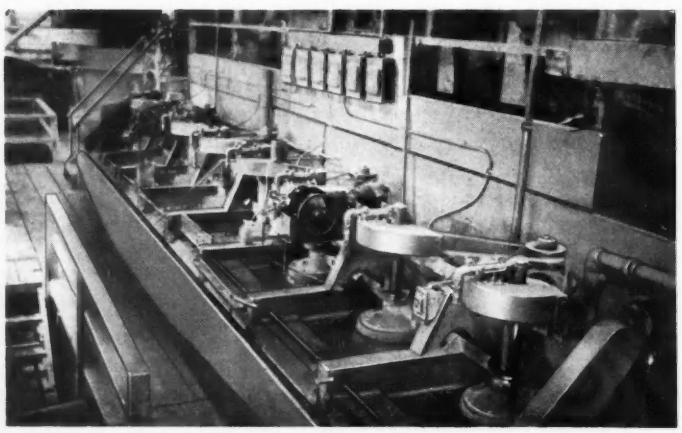


Fig. 6.—Kraut flotation cells at the plant of Lava Cap Gold Mining Co., Ltd., California.

Even though the particles of gangue-slime do not form coatings on the minerals, they often have a strong tendency towards adsorption at an air-water boundary, and will attach themselves to bubbles in the flotation cells and enter the froth, lowering the grade of the concentrate that comes off the machine. The use of an appropriate disperser will keep the gangue-particles

in the water-phase and prevent their concentration at the bubble-surfaces.

The reagents mentioned in the preceding pages are those that are commonly employed in modern practice. A large number could be added if a complete list were required, but they would consist mainly of obsolescent reagents and those which are still experimental. It is outside the scope of this article to include the full range.

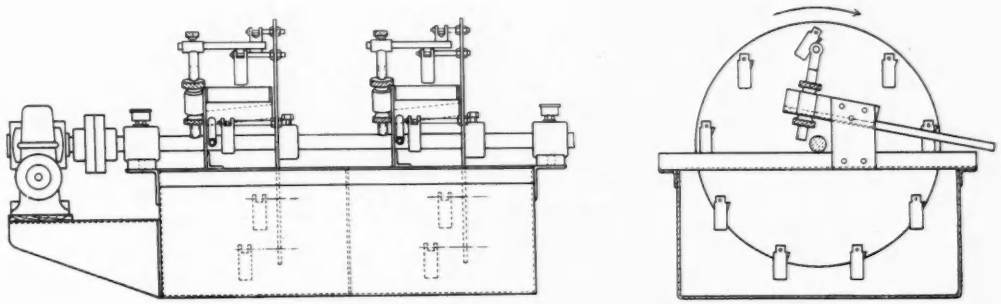


Fig. 7.—Tipping-cup type reagent feeder.

REAGENT FEEDERS.

Flotation is a continuous operation, and the reagents must therefore be introduced into the circuit continuously at the points where they are required. Such reagents as lime, soda ash and copper sulphate, which are usually needed in considerable quantities (1—5 lbs. per ton of ore), can conveniently be added in the solid form, the apparatus employed for the purpose consisting of a small rubber conveyor-belt, 6—10 inches wide, which runs under a bin containing the reagent. The belt is motor-driven through a variable-speed device so that the amount that it draws out of the bin can be altered to meet changing conditions. This feeding device has not proved satisfactory for chemical promoting reagents, which are required in much smaller amounts (0·05—0·2 lb. ton of ore), and the usual practice is to make them up into 10 or 20 per cent solutions and introduce them into the circuit by means of a special mechanically-operated feeder; the use of drip valves is unsatisfactory because of their tendency to choke. The same feeder also serves for the addition of the frothing oils.

The liquid reagent feeder usually employed is of the tipping-cup type illustrated in fig. 4. It consists of a tank divided into as many compartments as there are reagents to be added. On the tank is mounted a shaft carrying a number of metal discs, one for each compartment. Round the periphery of each disc are fixed nine bolts of three different lengths, on each of which is suspended a small metal cup so mounted that it can swing freely without being able to move laterally along the bolt. The shaft and discs are driven by a small motor at ½—4 r.p.m. Mounted at the side of each compartment is a horizontal tripper-arm, which can be regulated in a vertical direction to tip the cups on the disc to any required degree as the rotation of the disc carries them past the arm. The arm can also be moved laterally so as to tip three, six, or nine cups.

Each compartment is filled with a specific liquid reagent or solution. At the lowest point of their travel the cups are submerged in the liquid contained in the compartment. They are then carried up by the rotating disc, until, at their highest point of travel, they reach the tripper arm, which tips the required amount of liquid out of the cups as they pass it; as explained above, it can be set to tip three, six, or nine cups according to requirements. The liquid falls into a trough placed beneath it, from which it can be piped to any required point. The feeder thus has a very wide range of adjustment, since it can be set to deliver any quantity of reagent from a few drops per revolution to the full contents of nine cups. The discs can be made of any size to suit the capacity of the flotation plant; they are normally from 15 to 30 inches in diameter.

The apparatus is usually mounted on a platform well above the level of the other machines in order to provide sufficient fall to enable the reagents to be delivered to any point in the flotation section of the plant. The additions are normally made to the conditioning tank, to the first cell of the flotation machine, and to any other cell where the reagent may be required. These machines, and the manner in which they function, will be described in the next article.

Low Temperature Warming Systems.

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There are many designs of direct electric heating equipment available for warming occupied rooms, but all such equipment falls into two classes : either as convectors or low temperature radiators.

In the following article the author discusses the heating of rooms warmed by either of these forms of heaters, and also the effects of warming upon human comfort.

INTRODUCTORY.

IT may seem superfluous to state that the purpose of warming buildings is to prevent the occupants from feeling cold, but emphasis on this point is desirable, as the provision of comfortable conditions, from a heating point of view, entails many more considerations than the mere provision of a quantity of heat capable of maintaining the air in a room at constant temperature.

The method widely used at the present time of determining the heat demand of a room is to calculate the heat transmitted through room boundaries for a definite temperature difference between inside and outside air with an allowance for some accepted but purely arbitrary rate of ventilation, together with a further allowance for exposure or aspect.

Although this method has the virtue of simplicity, it is an indirect method and bears little relationship to the actual duty of the heating equipment. Experience has, however, proved it to be most satisfactory if not scientifically accurate. A clearer understanding of what constitutes human comfort and a recognition of the part played by radiant heat indicate that some more direct methods of determining the heat required for a room is needed; but it has to be remembered that because a method is old it is not necessarily bad; and if it is new it is not necessarily good. Further, any other proposed method must serve some years of apprenticeship before it can claim to be as commercially satisfactory and simple as that in use at present.

An equally simple method of equating the radiant temperatures of the whole of the surface within a room has been suggested. Admirable and ingenious though this method is, the fact still remains that a room is an enclosed space which must be maintained at a higher temperature than the outside air and is therefore subject to heat loss. What is really needed is some definite standard to indicate the extra comfort obtained by the use of low temperature radiation as distinct from the temperature shown on a thermometer which is not primarily capable of measuring radiation.

HUMAN COMFORT.

It is not proposed in this article to attempt to define physiological comfort—even if such a definition is possible—but from a warming point of view the human being is a warm moist body and as such loses heat by radiation, convection and evaporation, in exactly the same way as any other moist surface.

Much research has gone to establishing the normal rate of heat loss which must be kept within reasonable limits if discomfort due to cold or overheating is to be avoided.

The clothed human body has an average surface temperature of about 75°F. and the losses, using Rubner's figures for an average man in sedentary occupation and in comfortable surroundings are :—

Radiation—195 B.Th.U's per hour
Convection—138 B.Th.U's per hour
Evaporation— 92 B.Th.U's per hour

TOTAL—425 B.Th.U's per hour

Loss by radiation is proportional to the temperature of the surrounding surface; loss by convection to the ambient air temperature, and loss by evaporation, to a large extent, to air velocity. If, therefore, the body is surrounded by cold walls the radiation loss increases. If the ambient air temperature is low, the convection loss increases.

Within limits, any increase in one component of heat loss can be counterbalanced by a reduction in the other, but these limits are fairly narrow. A room with low air temperature and high wall temperature is apt to produce a feeling of stuffiness, while a room with a high air temperature and a low wall temperature is productive of discomfort due to excessive drying or evaporation at the skin surfaces. The curve in fig. 1 represents as nearly as possible the amount of variation permissible in either factor. These statements regarding high air temperatures apply to systems where the relative humidity of the room air is not kept constant.

From the foregoing remarks it will be seen that for ideal conditions, not only must a certain air

temperature—and possibly velocity—be maintained, but the temperature of walls and windows also controlled. Naturally such a procedure is a practical impossibility but it is these considerations which have led to low temperature electric heating installations being divided into two classes.

One type of installation employs either electrically heated hot water radiators, convectors or tubular heaters and is generally known as a convection heating system. The other employs large flat panels and claims to be heating by radiation. These panels are used in either ceiling, wall or floor position. Strictly speaking, however, only an installation employing ceiling panels can lay claim to heating by radiation and all types of convection heating appliances give much of their heat by radiation.

It is of interest to consider the characteristics of each form of heating in the light of the needs of physiological comfort.

WARMING BY CONVECTION.

The mechanics of heat loss from a heater to air in a room by natural convection are that cold air coming in contact with a hot surface absorbs heat. In absorbing heat it becomes less dense and rises in a vertical stream away from the heater. The continued process results in a continual circulation of warmed air throughout the room.

Warm air coming in contact with cold walls communicates some of its heat to the walls. This heat is conducted through the fabrics of the building and is lost at the outer face. As the wall temperature rises it has less cooling effect upon the air. The air temperature rises until a steady state is reached in which the loss through the building fabric is the same as that given to the air by the heater. In a well designed system this steady state is reached when the conditions upon which the load was originally calculated (say 65°F. internal temperature with 32°F. outside) are prevalent.

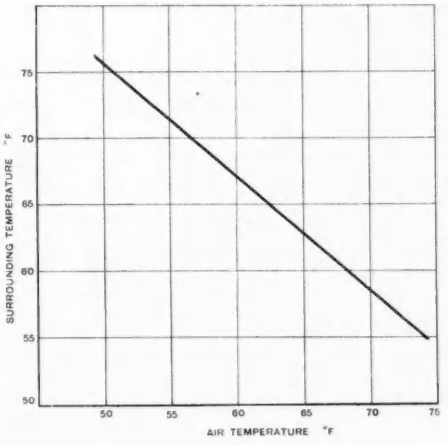

Fig. 1.—Approximate variation in air and surrounding temperature for comfortable conditions.

The co-efficients used for calculating heat loss from rooms are overall air to air co-efficients and are made up of factors governing the rate of heat flow into a wall, the rate of heat flow through the wall fabric or thermal conductivity and the rate of emission from the outer face, the whole expression being :—

$$K = \frac{1}{\frac{1}{E_1} + \frac{d}{k} + \frac{1}{E_0}}$$

Where K = Heat transmitted through wall in B.Th.U/sq. ft./hour/degree diff. between air temperature.
E_1 = Rate of absorption of heat at inner face in B.Th.U/sq. ft./hour/degree diff.
E_0 = Rate of emission at outer face.
d = Thickness of wall in inches.
k = Thermal conductivity of material used.

All the factors embodied in this expression remain constant except E_0. The value of this for most building materials is 4·5 but for approximately still air conditions only. The effect of rain or wind is to increase the emission at the outer face of the wall and in consequence the rate of conduction from the inner face of the wall. In thermostatically controlled systems the internal air temperature is approximately constant. There is, therefore, a fall in inner wall temperature if the outside temperature falls. The heat storage of the building fabric delays for a time any effect upon air temperature but ultimately the room temperature also falls. Heating equipment must therefore be capable of counteracting losses greater than those given by the ordinary loss co-efficients.

It is clear that the inner air temperature of a room is always higher than that at the inner face of the wall, windows, ceiling and floor. The magnitude of this difference clearly depends upon the thermal conductivity of the wall. With average brick construction, and an outside temperature of 40°F. a room with an air temperature of 65°F. will have a wall temperature of the order of 58°F. when the steady state has been reached. Under these conditions the inner face of a window would be at about 52°F. If the outside temperature fell to say 30°F. the inner face of the wall will fall to about 54°F. and in the case of the window to 42°F.

Bearing in mind the fact that human comfort depends upon maintaining a certain total heat loss and that the radiation loss rises with a decrease of wall or surrounding temperatures, it is clear that to restore the balance in the above room by decreasing the convection loss, a higher air temperature is

needed. This consideration assumes great importance when dealing with rooms having a very large window area.

The effect of cold walls in a room is to reduce the effective temperature. Various types of instruments representing the human body have been devised which are sensitive to radiation and are used to measure the resultant of the air and wall temperature. The result always indicates that the room temperature as distinct from a thermometer reading as far as the occupant is concerned approximates to the mean of the two values. For a room at 60°F with walls at 55°F. the effective temperature of the room is only about 58°F. Here then is the reason for the widely held belief that an air temperature of 60°F. is not sufficient. In actual fact, however, an air temperature of 60°F. is quite satisfactory provided that the building itself is not cooler. Approximate conditions are shown in fig. 2.

The effect of walls upon conditions of comfort is best illustrated by comparing the conditions of a panelled room with one having solid walls. In panelled rooms there is usually an air gap between the inner face of the panel and the wall. This air gap acts as an insulator to the panelling and if the panelling has low thermal capacity its surface temperature approaches much more closely to the air temperature than do solid walls. The result is a higher mean temperature generally obtained with less expenditure of energy.

The use of the panel type of furnishing also has many advantages from the point of view of intermittent warming. With the same installed load it will be found that comfortable conditions in such a room are attained in less than half the time required for a room with solid walls.

EFFECT OF CONVECTION CURRENTS.

The quantity of heat lost per hour per square foot by a surface due to natural convection only is given by—

$$H_c = \cdot 3\,(T-t)^{1.25}$$

Where T = surface temperature
t = air temperature
H_c = heat loss by convection only.

Also the velocity of the convected currents is proportional to the temperature excess in the air when leaving the upper limit of the heater. This temperature is obviously proportional to the time period in which the air is in contact with the heater. Hence the greater the vertical dimension of the heating surface or the greater the temperature difference between heater surface and air, the greater the convection current velocity.

As the convection currents rise in a vertical direction the ceiling of a room first becomes heated. Air circulation causes a temperature rise at floor level but there is always some temperature gradient within the room. As would be expected this gradient is greatest with high velocity convection currents which result from the use of tall or high temperature surfaces.

High temperatures at ceiling level, in the case of single storey buildings, are responsible for excessive heat loss through roofs; but to some extent a high ceiling temperature is useful for when the ceiling itself becomes heated, it radiates downwards to the floor, raises the floor temperature and provides an additional component of radiation. In storeyed buildings, excessive ceiling loss contributes towards the warming of the floor above.

It is well known that although there may be no change in air temperature the draught of a fan on a hot day has a welcome cooling effect. This is because the rapid movement of air across the skin increases the rate of evaporation from it, the evaporation being accompanied by extraction of heat. The same effect takes place in a heated room with either high temperature or high air velocity due to convection currents. The cooling is somewhat less pronounced but it is one of the disadvantages of a high temperature heating surface.

TUBULAR HEATING INSTALLATIONS.

One of the oldest and most popular types of electrical installation is that which uses 2-inch steel tubes loaded to 60 watts per foot. These tubes are usually arranged around the room and have a working surface temperature of approximately 190°F. They are classed as convectors but it is, of course, quite impossible to obtain the whole of the emitted heat as convection. Radiation also takes place and has a value of approximately 50 per cent of the total.

Of this quantity of radiation some 60 per cent is radiated direct to the floor and walls of the room. Some of this in turn is re-radiated to the room, but as tubes are frequently fitted in single, double or treble tiers, any attempt to evaluate the loss direct to the wall under differing conditions is not possible. It can be stated with certainty, however, that the loss is about 10 per cent of the total emitted as radiation and convection.

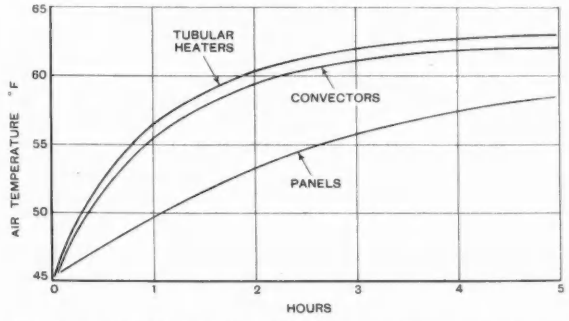

Fig. 2.—Relative rate of increase of air temperature with tubular heaters, convectors and panels.

It has been mentioned that the temperature gradient in a room depends upon the velocity of convection currents. With a horizontal 2-inch tube the temperature difference between air approaching and leaving the tube is very small; hence low velocity air currents arise. This results in a very small temperature gradient between floor and ceiling. In any well warmed room equipped with tubes there is seldom more than about 1°F. difference in air temperatures in any part of the room.

Tubular heaters are frequently mounted in banks or tiers. The effect of using this arrangement is to produce a higher surface temperature on the tubes on account of the interchange of radiation between them, while such an arrangement also produces slightly higher velocity convection currents without materially affecting the temperature gradient throughout the room.

Another advantage of low velocity convection currents is that the rate of heat exchange between warm air and cool wall is low. In all rooms warmed by natural convection there is at the wall surface a film of stagnant air through which the heat passes by conduction only. Still air is an excellent thermal insulator so that within limits the thicker the air film the lower the rate of heat loss. High velocity air currents tend to sweep away the protective film and produce a scrubbing action between the moving warm air and the wall, giving an increased rate of heat transfer and, therefore, wall temperature.

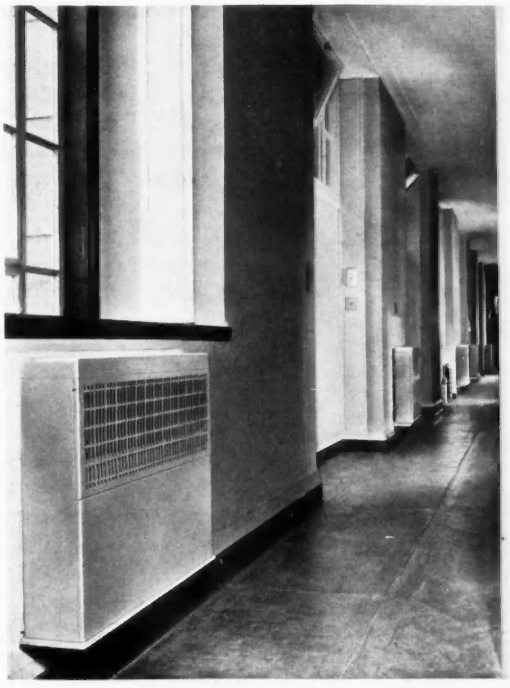

Fig. 4.—Wall type convectors controlled by thermostats fitted in wall recesses.

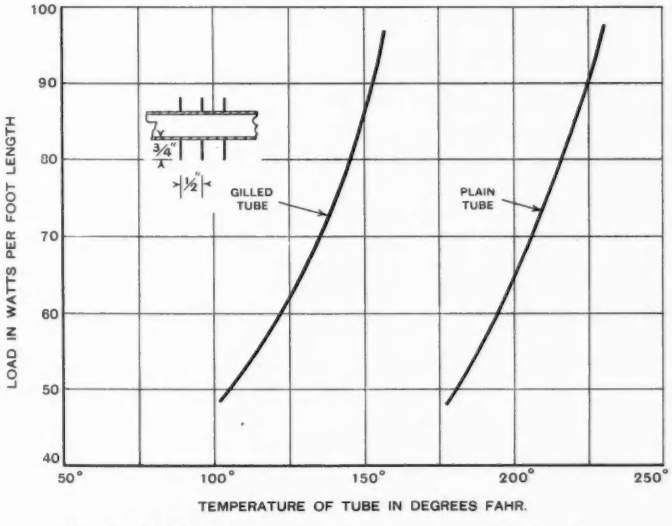

Fig. 3.—Variation of surface temperature with loading for plain and gilled tubular heaters.

Against this advantage must be set the disadvantages of slow rate of temperature rise in the walls for, as has been indicated, it is very necessary for the building to become heated to ensure a high mean room temperature.

POSITION OF TUBES.

It is sometimes advocated that where two or more tubes are required, they be best distributed around the room rather than fitted—assuming space is available—on the cold or exposed side of the room. Further, it is sometimes stated that when fitted to an inside wall some of the direct loss to the wall is eliminated.

As far as economy in operation is concerned it matters little whether an outside or inside wall is used but to fit the tubes to the cold side—which is generally below a window—has definite advantages. The room temperature gradient for tubes fitted to the window side of a room is appreciably lower than if an inside wall is used.

A further reason for fixing tubes against the cold walls of a room is that the comparative high temperature radiation from the tubes comes from approximately the same source as the low temperature radiation from the windows. These two tend to cancel each other as far as a receiving surface or occupant in the centre of the room is concerned. If the warmed side of the room is used the receiving surface would receive high and low temperature radiation on different sides.

A further incidental advantage accruing from

using, say, one double tier instead of two separate tubes is that the former is generally provided with a common terminal box, and wiring is thus simplified.

In many buildings such as garages, workshops or shops, lack of accommodation often results in tubes being fitted in an overhead position. The position selected is often below north lights. Tubes fitted in this position can, of course, be loaded to 90 watts per foot with the consequent increase in surface temperature.

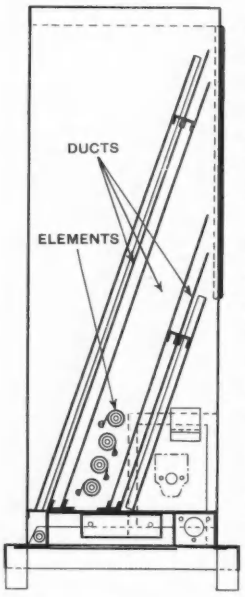

Fig. 5.—General arrangement of baffles and air ducts in G.E.C. convector.

Tubes fitted below window lights in an overhead position are effective in checking down draughts but they produce a big temperature gradient and roof loss and are about 15 per cent less efficient than if mounted in the floor position. If a simple inverted wood trough is fitted above them, their efficiency is increased by about 30 per cent. The reason for this is that the trough becomes warmed and acts as a radiator directing heat down to the working levels.

CONVECTOR INSTALLATIONS.

Convectors are, in brief, plain or ornamental boxes containing heating elements. This type of heating equipment is extremely useful where there is a lack of wall space as it permits relatively high loadings to be accommodated in a small area. In most convectors the heating element is of the low temperature type fitted in an air shute. This air shute effectively baffles direct radiation and prevents a dangerous temperature at the casing surface.

As is to be expected with a high concentrate of load, the temperature and velocity of the convection currents are high. Actual results depend upon the type and free area of the ornamental grid fitted at the outlet but average values of velocity and temperature are about 160ft. per minute and 180°F. respectively. This velocity produces a steeper temperature gradient within the room than tubular heaters, but it is of some advantage where rapid pre-warming and the provision of high mean room temperature are required.

In general, with equal heating periods the walls of a room, heated by convectors, become warmed to a higher temperature than with tubes, and although the actual air temperature may be lower, the mean temperature, due to warm walls, has a higher value. These remarks apply to rooms with a low rate of ventilation. As the rate of air change increases, however, the advantages of convectors disappear as high velocity convection currents and steep temperature gradients encourage the rate of air change. In naturally well ventilated rooms tubes have an advantage.

In spite of its name this type of appliance gives considerably more of its heat by radiation than tubular heaters. The air chute backing the outlet grid, and the grid itself, become heated and in turn they emit low temperature radiation to the lower levels of the room. To some extent this tends to correct the temperature gradient within the room and adds materially to the resulting comfort.

Convector heaters are as well suited to thermostatic control as tubes, but due to the slightly larger thermal capacity of the mass of the convection there is apt to be an overlap of air temperature when compared with the cut-off temperature of the thermostat. The temperature of a room equipped with convectors may therefore vary by from 5° to 7°F.

Some designs of convectors are equipped with thermostats in which the heat sensitive element is in the lower part of the metal box. This is a very convenient arrangement, but it results in an uneconomical installation and is productive of a higher ceiling temperature, for the thermostat is in the coolest part of the room and is protected from, and therefore cannot take advantage of, the radiation from a hot ceiling or from the outside of the convector itself. In all installations the best level for

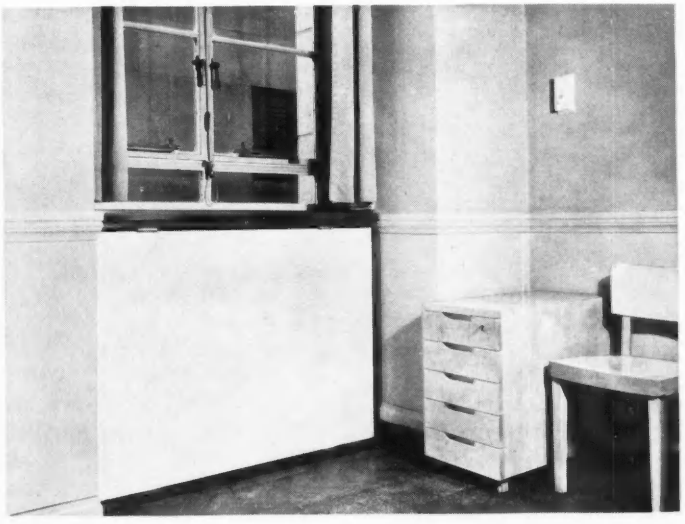

Fig. 6.—Wall type heating panel mounted underneath a window.

thermostats is at breathing level or about 5ft. above the floor level.

WARMING BY RADIATION.

Radiation is emitted from heat sources at all temperatures; it is easily recognized in the case of an electric fire mainly because of its high intensity. With a high temperature source of radiation, however, the space immediately in front of the heater gives rise to considerable discomfort, but with low temperature radiation this particular objection is eliminated.

It may be said of heating by low temperature radiation that it is an attempt to warm an occupant of a room rather than the room itself. It is also a direct attempt to deal with the larger component of heat loss from the surface of the clothed body and to use a natural phenomenon ignored in so-called convection systems.

Heat loss or exchange by radiation is proportional to the nature of the emitting surfaces and also to their respective absolute temperatures; the high temperature surface always emitting to the lower. If two surfaces are synthermal then there is no heat exchange between them.

The clothed human body has an average surface temperature of about 75°F. If, therefore, the surrounding surfaces are at 50°F., heat loss takes place from the body; if the surroundings are at 80°F. then heat is received.

It is perhaps not permissible to apply an exact thermal equation to heat loss from the occupant of a room but it is at least instructive. The surface area of the body is generally assumed to be about 20 sq. ft. From this it can be shown that if Rubner's figures for convection loss, with the body at 75°F., are to be maintained, then the air temperature should not be less than 62°F. From the radiation formula the surrounding surfaces must not be less than 60°F.

In ordinary rooms, however, all boundaries will not rise to the same temperature. Window surface

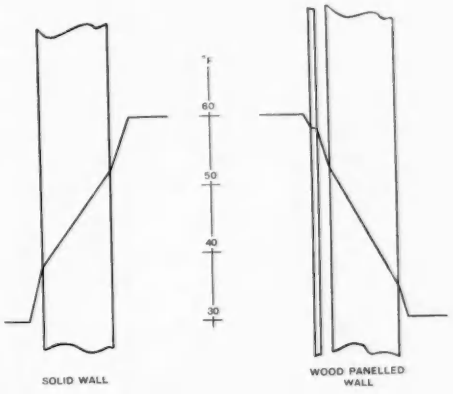

Fig. 8.—Temperature gradients through solid and panelled walls.

for example has a value of about 40°F. Radiation loss between the body and window surface is large. In order, therefore, to compensate for the low temperature of the windows, the wall temperature must be proportionately higher to give an average surrounding temperature of not less than 60°F.

In rooms heated by convection it is the air which heats the building fabric, but it is seldom possible to raise their temperature above about 58°F. With radiation warming, however, heat is exchanged direct between say a heating panel and the walls, floor and furniture surface. As these become warmed they warm air by convection, hence the surrounding surfaces have a higher temperature than air.

This is the opposite state of affairs to convection warming, and it is claimed for radiation warming that a smaller expenditure of energy takes place for the same duty. Whether this claim is valid or not it is an established fact that when the primary source of heat in a room is low temperature radiant equipment, correctly installed, the mean room temperature is appreciably higher without an increase in the air temperature.

An ordinary thermometer records only air temperatures but such instruments as the globe thermometer (which consists of an ordinary thermometer, the bulb of which is surrounded by a blackened copper ball about 6ins. diameter) and the eupathescope measure the extra temperature given by radiation from surrounding surfaces. If warming by radiation is to develop, some standard of difference between these two readings is needed.

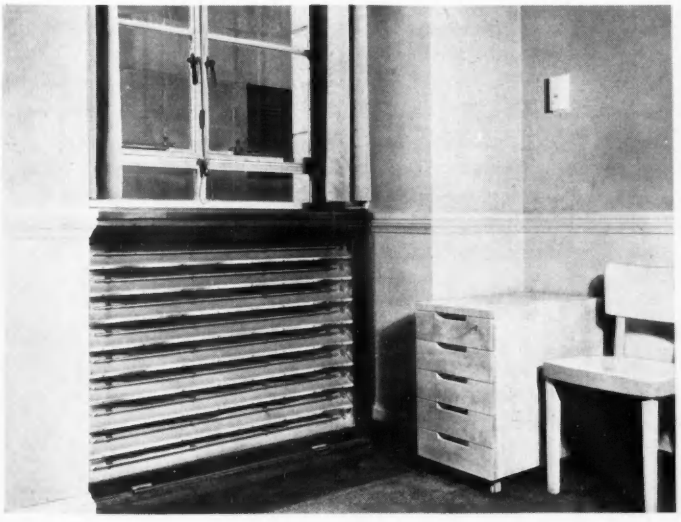

Fig. 7.—The wall panel shown in fig. 6 with its "T" front plate removed.

If an installation depends for its success partly upon radiation, and its radiation is not recorded on a thermometer, no proof is afforded that the installation is satisfactory; it is necessary to obtain

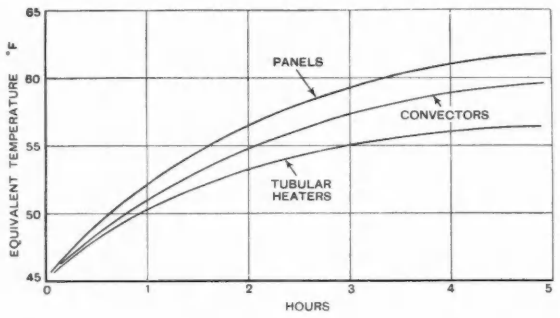

Fig. 9.—Comparative equivalent temperatures of an enclosure taking radiation into account.

the opinion of the occupants of the room. As individuals re-act in varying degrees there is no definite standard to which to work. The effect of radiation on equivalent room temperature is shown in fig. 9.

Warming by radiation has come to be known as panel warming solely because the type of heaters used have large flat surfaces which are obviously better adapted for the free emission of primary radiation.

It has been stated that only rooms heated by ceiling panels can be described as warmed by radiation, for in this place a hot surface is in the worst possible position for encouraging loss by convection. Convection loss cannot be entirely eliminated even in the ceiling position but its value is relatively small when compared with its radiation component. Wall panels in a vertical position are widely used. They are as a rule easier to install and permit a slightly higher loading per square foot for the same surface temperature than a ceiling panel. The reason for this latter is that while the radiant emission remains constant the convection loss is increased.

In the wall position the direct radiation from panels is often screened by furniture in the room. This naturally reduces the efficiency of the system and, if the total heat emitted from the panel is regarded as contributing only to air temperature, the full value of using a flat panel surface is lost. It is always desirable that free radiation of a panel should in no way be screened, for it constitutes one of the prime contributions to comfort throughout the whole of the room. Low temperature floor panels are also used but it is not desirable to have a floor temperature higher than 70°F. In warming systems this latter point needs careful attention for the ceiling of a ground floor is the floor of the room above. Quite apart from the serious loss of efficiency due to back loss from a panel, excessive floor temperatures above are productive of discomfort. The criterion of a well designed panel is the limitation of back loss.

The same total quantity of radiation emitted in a given time can come from a small surface area at high temperature, as from a large area at low temperature. From a knowledge of exchange of radiation and the body temperature it is clear that a low temperature source is preferable. The minimum temperature is to some extent regulated by economic and practical considerations. In electrically heated panels, temperatures of about 150°F. are used and the load per square foot varies with the position.

Some tests carried out at the G.E.C. Research Laboratories on panels designed for an installation at the London University are shown in fig. 10. It will be noticed that total loss is given. The components of radiation and convection can be split up as indicated by the tests of Griffiths and Davis

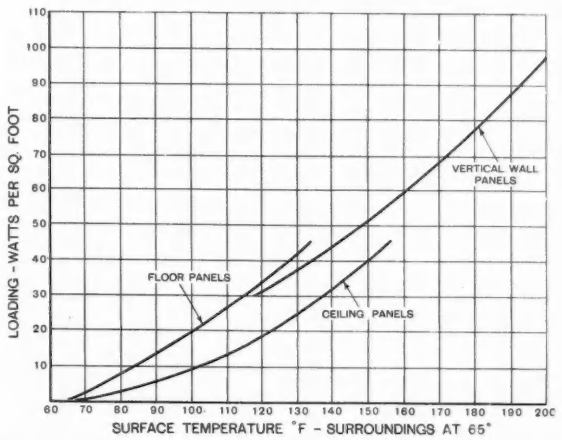

Fig. 10.—Variation in surface temperature of sheet steel panel with respect to loading and position.

at the National Physical Laboratory. These tests indicate the following:

	Radiation	*Convection.*
Vertical wall panel heater ..	35%	65%
Ceiling panel heater ..	60%	40%
Floor panel	30%	70%

THERMOSTATIC CONTROL AND CONSUMPTION.

It was stated earlier in this article that the load installed in any room, irrespective of the type of heating employed, is designed on the basis of a minimum external temperature of 32°F. and an internal temperature varying from 55° to 65°F.

It is common experience in England that there are not more than about six days per year in which the outside temperature is constantly at 32°F. It will be found, in fact, that the average winter temper-

ature approaches 43°F. Instead of having to maintain a temperature difference of 33°F. the equipment need only maintain a temperature difference of 22°F, as shown by the curve in fig. 11. This means, of course, that the heat demand over a season, depending on the selected internal temperature, is between 60 and 66 per cent only of the maximum possible, provided the inner air temperature is automatically controlled.

The heating season, using 24 hours heating, is reckoned as 5,000 hours or seven months continuous heating; thus a continuously connected load of 1 kW would account for between 3,000 and 3,300 units per year if under thermostatic control in an enclosed space. There are, however, other factors which materially reduce this consumption, for thermostats are sensitive to heat from any source.

It has been stated that the human body emits heat; this emission is at the rate of approximately 100 watts per hour per person. This heat contributes towards warming the air in the room which ultimately affects thermostat operation in favour of reduced energy consumption at the consumer's meter. An office of say 2,000 cubic feet with three people at work for 8 hours, receives some 2·4 kWh of incidental heat during that period. On an average basis this is equal to about 1·5 hours loss for that size office.

Another important factor is that the heating season is also the lighting season and in these days of increasing light intensity larger lighting loads are being installed. The heat emitted by lamps has material effect upon the consumption of the heating system. This is particularly so where indirect lighting is used, for in these installations loads may exceed five watts or 17 B.Th.U's per square foot of floor area, 1·5 watts per square foot is a common figure.

The basis upon which the maximum load for a room is calculated is the loss of heat through the walls. The rate at which it is received by the inner wall face is practically constant at 1·5 B.Th.U's per hour per degree difference. The rate of loss at the outer wall is for approximately still air conditions 4·5 B.Th.U's per square foot per degree difference. The value varies with weather conditions; rain and wind increase the loss through walls and windows, while the effect of sunshine is to decrease it; sunshine may in fact cause an inward flow of heat. In general, however, these influences cancel each other leaving the basis of calculated heat loss, together with average temperature difference, to be used for determining unit consumption.

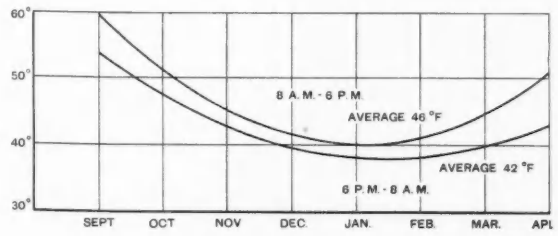

Fig. 11.—Average monthly variation of temperature in winter.

When a room has thermostatic temperature control it is assumed that the internal temperature is constant. This is an inaccurate assumption for if a thermostat cuts off at say 62°F. the air temperature must fall before the heater circuit is re-made. The overlap temperature in a thermostat may be as close as 1·5°F. but, low though its thermal capacity may be, there must be some lag and temperature difference between air and thermostat before the heat sensitive mechanism of the thermostat can produce enough power to operate the switch. There is, therefore, some 3° to 5°F. difference in the room air temperature. If a thermostat cuts off at say 62°F. and in at 58°F. the average air temperature is 60°F. and not 62°F. The average temperature difference is reduced by some 10 per cent due to this cause and, therefore, the unit consumption is reduced.

Very few direct electric heating systems are in use continuously throughout the season. Heating is generally cut off at week-ends. The season's consumption and reduction of heating hours, due to incidental forms of heat, is reducible to an average value of about 2,000 units per kW of loss. This figure is principally to show the effects of incidental heat sources upon the unit consumption of a system when controlled by room thermostats. It cannot be generally applied as a large part of the heat consumed by a room is required for warming air used for ventilating purposes. This quantity naturally depends upon the rate of air change within the room and is at a rate which is seldom equal for any two rooms. Such a figure must, therefore, be taken as a guide rather than a fact.

The foregoing consumption refers to 24 hours heating but with electric heating installations it is more customary practice for office blocks at least to use daily heating, the installation being switched on each morning. This practice gives considerable economies in operating costs. Direct comparisons on the same buildings have shown that the quantity of heat required for a season's intermittent use is but 75 per cent of that required for continuous warming.

The figure of 2,000 units per kW of loss can therefore, be reduced to 1,700 units, which can be taken as being in reasonable agreement with results obtained from practice.

Although there is an appreciable saving due to the use of intermittent warming it does not follow that the load installed to maintain a temperature difference will be capable of giving the necessary temperature rise in a reasonably short period. In view of this it is interesting to consider the con-

ditions in an intermittently warmed room from a stand point of human comfort; bearing in mind the fact that comfortable conditions depend on a warmed building fabric.

INTERMITTENT WARMING.

When the heat is turned off at night a room immediately begins to cool, mainly due to loss of heat through windows. The air temperature cools to a level below that of the walls and, the flow of heat being reversed, the walls tend to warm the air. The morning pre-heating must be capable of restoring the total quantity of heat lost from the walls and air during the night.

The quantity of heat so lost depends upon the cooling surface. A corner room with two exposed walls will fall to a lower temperature than a room with one exposed wall but as the corner room will contain more heating surface for normal duties than a room with one exposed wall, the approximate re-heating time will be the same.

It is customary in intermittently (or actually any) heated buildings to close the windows overnight. This means that during the morning pre-warming, the heat normally used for ventilating purposes is available to assist in warming the fabric of the room.

In a room of 2,000 cubic feet the allowance for heat losses only would be 1,750 watts and for ventilation about 700 watts. If the windows are closed, there is already in this room an increase of 40 per cent over the nett loss available for pre-warming. Unfortunately this total quantity of heat is not sufficient for the heat delivered during, say, a two hour pre-warming period which must be equal to the total loss in say 10 hours.

Allowing for a steadily decreasing rate of cooling this total is equal to about four hours normal loss at full load, or, in the room quoted above, some 7 kW, excluding ventilating. To restore this in two hours the load must be 3·50 kW, which is equal to a margin of 50 per cent above the total installed load.

In large buildings it would not be an economic proposal to install such a high load. Nevertheless these are the conditions which apply to a room and have to be met in an intermittently warmed room. It is generally considered, however, that a two hour pre-heating period is satisfactory for most purposes when considered from the point of view of average winter temperature.

The most commonly employed formula for estimating the additional heat required by intermittently warmed rooms is that given by Rietschel and is as follows :—

$$H = \frac{\cdot 0625\ (n-1)}{Z}\ W$$

Where H = B.Th.U's to be added to that calculated by the heat-loss method.

W = B.Th.U's calculated by heat-loss method, including ventilation.

n = Number of hours during which rooms are unheated.

Z = Time in hours allowed for pre-warming.

It should be borne in mind that this addition is for regular heating in which circumstances a pre-heating period averaging two hours would be expected; but with offices not warmed at week-ends the load would still be inadequate to give the necessary temperature rise on Monday morning.

In buildings with thin walls the steady heat losses are high but the thermal capacity of the building fabric is small, hence pre-heating can be carried out rapidly. In a solidly constructed building, however, not only are large quantities of heat absorbed but the rate of absorption is low, for the temperature head driving heat into the walls is necessarily also low. If the advantage of a thin wall building, as far as pre-heating is concerned, is combined with the insulating effect of solid walls, as is obtained in a panelled room, the pre-warming of rooms is considerably simplified as shown in fig. 8.

In rooms warmed by panels comfortable conditions are achieved slightly more quickly than with convection warming as the warm radiation tends to neutralise the cold radiation from the walls, but the actual air temperature rise is always considerably slower. This is due to the fact that air warming is a secondary process only. Theoretically, at least, air is not heated by radiant heat.

The rate of pre-warming a room by convectors with a normal load, may be taken as approximately 5° per hour. With heating panels the rate of warming rises to something of the order of 8° per hour but at a decreasing rate as the temperature approaches maximum.